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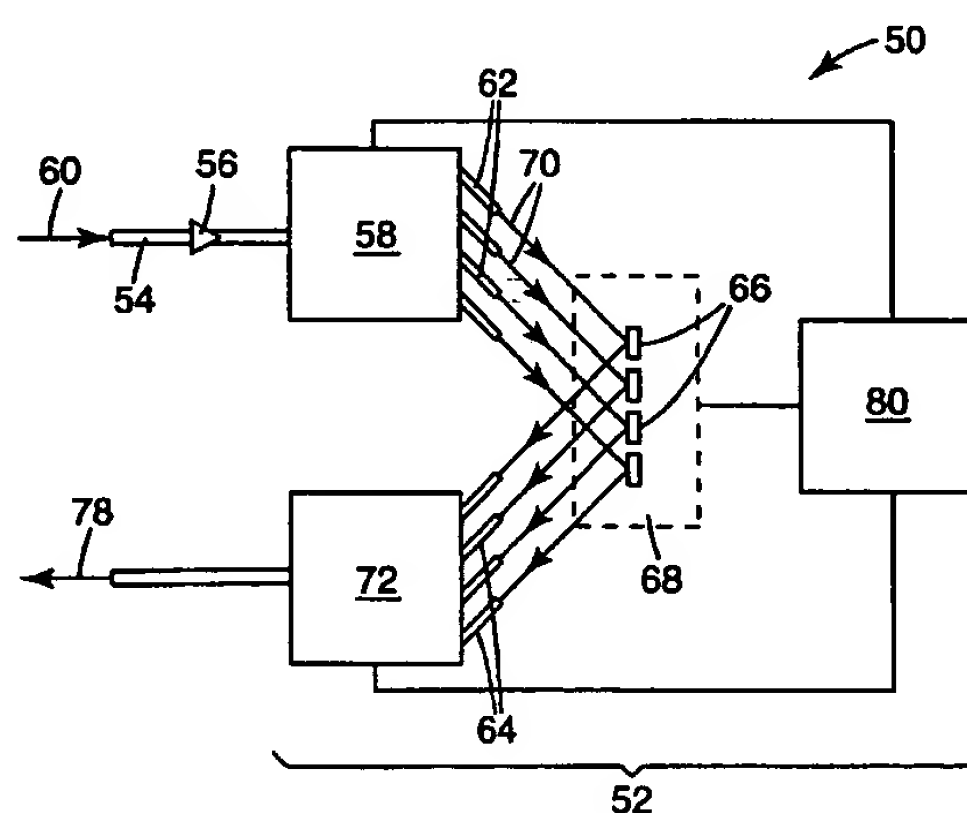
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(54) Title: MEMS-BASED WAVELENGTH EQUALIZER



(57) Abstract: A wavelength specific optical equalizer for selectively attenuating discrete wavelength signals contained within a wavelength division multiplexed signal without affecting the adjacent signals. The wavelength equalizer includes a demultiplexer adapted to separate a wavelength division multiplexed signal into a plurality of discrete wavelength signals and to direct each of the discrete wavelength signals along a plurality of first optical paths. A micro-mechanical device comprising at least one micro-mirror is optically coupled with each of the first optical paths. A plurality of second optical paths is positioned to receive the discrete wavelength signals reflected from the respective micro-mirrors. At least one actuator is mechanically coupled with each of the micro-mirrors. The actuators are adapted to selectively displace one or more to divert at least a portion of the discrete wavelength away from the corresponding second optical paths. The orientation of the micro-mirror determines a signal strength of the discrete wavelength signal reflected to the corresponding second optical path. A multiplexer is provided to combine the discrete wavelength signals in the plurality of second optical paths into a reconstituted wavelength division multiplexed signal.

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MEMS-BASED WAVELENGTH EQUALIZER

5 The present invention relates generally to a MEMS-based wavelength specific equalizer, and in particular, to a method and apparatus for using a MEMS-based device to steer and manipulate beams of light in a wavelength equalizer.

 In wavelength division multiplexed ("WDM") networks, a single optical fiber often carries multiple independent data channels, wherein each data channel is assigned to a
10 distinct optical wavelength. In optical telecommunication networks, it is possible that the different wavelengths do not have the same amplitude. For example, as signals propagate through a fiber optic network, the signals experience both transmission losses and coupling losses from point to point within the network. In order to compensate for transmission losses and coupling losses, the multiplexed signals carried by an optical fiber are often
15 amplified at various points in the network using an Erbium-doped fiber amplifier or the like.

 Erbium-doped fiber amplifiers amplify each optical wavelength contained within the multiplexed signal. However, the amplification gain provided by the Erbium-doped fiber amplifier is not uniform with frequency. Rather, certain wavelengths are amplified to
20 a much greater degree than are other wavelengths. As a multiplexed signal experiences multiple cycles of transmission losses, coupling losses and then amplification, the variations in intensity between different wavelengths grows. If not corrected, the uneven signal strengths may result in inter-channel cross talk and the loss of the data being transmitted.

25 In order to minimize non-linear effects in these amplifiers and to permit the use of common communication circuitry for all channels, it is necessary that the various wavelength channels have similar power levels. However, as various wavelengths are added or subtracted at various nodes in the network, the power levels of the various channels change, in turn changing the gain spectrum of the amplifiers. Such network
30 changes can be slow as when customers are added and removed or fast as when network traffic is dynamically rerouted for improved efficiency. Often the variation in power is

roughly monotonic in wavelength and can be adequately compensated by a monotonic change in attenuation as the wavelength changes, that is by a spectral attenuation tilt.

Systems and methods have been developed to compensate for the uneven wavelength dependent gain of Erbium-doped fiber amplifiers in optical fiber communications. One such prior art technique is to proactively compensate for the uneven gain of an Erbium-doped fiber amplifier by pre-emphasizing the input levels of signals carried by the optical fiber. Such a prior art technique is exemplified in "END TO END EQUALIZATION EXPERIMENTS IN AMPLIFIED LIGHTWAVE SYSTEMS" by A. R. Chraplyvy et al., IEEE Photonics Technology Letters, 4(4), pp. 428-429 (April 1993).

A second prior art technique to compensate for the uneven gain of Erbium-doped fiber amplifiers is to use in-line optical filters. The optical filters attenuate the wavelengths having the greatest degree of amplification, thereby creating more even signal strength across all the signal wavelengths. Such a prior art technique is exemplified in "TUNABLE GAIN EQUALIZATION USING A MACH-ZENHDER OPTICAL FILTER IN MULTISTAGE FIBER AMPLIFIERS", by R. Inoue et al., IEEE Photonics Technology Letters, 3(8), pp. 718-720, (April 1991). Also see U.S. Pat. No. 5,430,817 (Vengsarker).

U.S. Pat. No. 5,500,761 (Goossen et. al.) discloses a mechanical anti-reflection switch modulator ("MARS modulator") useful for optical power equalization. The MARS modulator is basically a Fabry-Perot cavity comprising the air gap between an optical membrane and a substrate. Modulation is based on voltage-controlled vertical movement of the membrane in relation to the substrate. The MARS modulator provides broad spectrum, high contrast reflection modulation at rates in excess of several million bits/second. A MARS modulator having low insertion loss and broad operating bandwidth particularly advantageous for optical communications applications is described in U.S. Pat. No. 5,870,221.

Referring to the drawings, FIG. 1 is a schematic cross section of a single unit MARS modulator of the type described in the Goossen patents. The device 9 comprises a substrate 10 and a membrane 15 spaced from each other to define a gap 20 between them. The substrate 10 is a conductive material such as doped silicon, and the membrane 15 comprises one or more layers of conductive material such as an overlayer 15a of silicon nitride and an underlayer 15b of polycrystalline silicon. The overlayer has an index of

refraction approximately equal to the square root of the substrate refractive index and the underlayer has an index of refraction approximately equal to the substrate refractive index. The thicknesses of 15a and 15b are each less than one-quarter of the operating wavelength λ . The membrane 15 and the substrate 10 are spaced apart by a peripheral support layer 12 of insulating material. Electrodes 30 and 31 permit connection of the membrane 15 and substrate 10, respectively, to the terminals of a bias voltage source 29.

The air gap 20 can be controlled by a bias voltage between the substrate and the membrane. Relative reflective maxima are produced when the gap 20 is an odd integer multiple of one-quarter of the operating wavelength λ . Minima are produced when the gap 20 is 0 or an even integer multiple of $\lambda/4$.

The present invention relates to a wavelength specific optical equalizer for selectively attenuating discrete wavelength signals contained within a wavelength division multiplexed signal without affecting the adjacent signals.

In one embodiment, the wavelength equalizer includes a demultiplexer adapted to separate a wavelength division multiplexed signal into a plurality of discrete wavelength signals and to direct each of the discrete wavelength signals along a plurality of first optical paths. A micro-mechanical device comprising at least one micro-mirror is optically coupled with each of the first optical paths. A plurality of second optical paths is positioned to receive the discrete wavelength signals reflected from the respective micro-mirrors. At least one actuator is mechanically coupled with each of the micro-mirrors. The actuators are adapted to selectively displace one or more of the micro-mirrors to divert at least a portion of the discrete wavelength away from the corresponding second optical paths. The orientation of the micro-mirror determines a signal strength of the discrete wavelength signal reflected to the corresponding second optical path. A multiplexer is provided to combine the discrete wavelength signals in the plurality of second optical paths into a reconstituted wavelength division multiplexed signal.

In one embodiment, the first optical paths comprise the second optical paths. That is, the discrete wavelengths are reflected off the micro-mirrors back down the first optical paths. A plurality of signal strength detectors is provided to detect the optical signal strength of the discrete wavelength signals. In one embodiment, a beam splitter is located along a plurality of the first optical paths. Signal strength detectors are optically coupled

to the beam splitter to detect the signal strength of the discrete wavelength signals. A controller is optionally coupled to the actuators and the signal strength detectors. The controller can selectively attenuate one or more of the discrete wavelength signals in response to a monitored signal strength.

5 The micro-mirrors and the actuators are preferably constructed on a surface of a substrate. The micro-mirrors can be attached to the surface of the substrate by a hinge, a gimbal or a torsional spring. The micro-mirrors are adapted to move through at least one degree of freedom.

10 The actuators are preferably thermal actuators. The thermal actuators comprise at least one hot arm having a first end anchored to the surface, a free end located above the surface, and a cold arm having a first end anchored to the surface and a free end. The cold arm is located above the hot arm relative to the surface. A member mechanically and electrically couples the free ends of the hot and cold arms. The member is positioned to engage with the mirror when current is applied to at least the hot arm. In one embodiment, 15 the thermal actuator comprises at least one flexure adapted to provide controlled bending. In another embodiment, the thermal actuator comprises at least one reinforcing member.

20 The micro-mirror reflects substantially all of the discrete wavelength signal from one of the first optical paths to the corresponding second optical path when the actuator is in an unactivated configuration. The micro-mirrors reflect only a portion of the discrete wavelength signal from one of the first optical paths to the corresponding second optical paths when the actuator is in an activated configuration. In one embodiment, the micro-mirror reflects substantially none of the discrete wavelength signal from one of the first optical paths to the corresponding second optical path when the actuator is in an activated configuration.

25 In another embodiment, the wavelength equalizer comprises a demultiplexer adapted to separate the wavelength division multiplexed signal into a plurality of discrete wavelength signals and to direct each of the discrete wavelength signals along a corresponding plurality of first optical paths. A plurality of second optical paths are positioned to receive the discrete wavelength signals. The micro-mechanical device 30 comprises a thermal actuator adapted to selectively divert at least a portion of the discrete wavelength from one or more of the first optical paths away from the corresponding

second optical paths. A multiplexer is provided to combine the discrete wavelength signals in the plurality of second optical paths into a reconstituted wavelength division multiplexed signal.

5 In one embodiment, the micro-mechanical device comprises a plurality of micro-mirrors mechanically coupled to a plurality of thermal actuators. In another embodiment, the plurality of first optical paths each extend along a surface on a corresponding thermal actuator. The second optical paths are optically aligned with each of the corresponding first optical paths, respectively, when the thermal actuators are in an unactivated condition. The first optical paths are optically diverted from each of the
10 corresponding first optical paths, respectively, when the thermal actuators are in an activated condition.

The present invention is also directed to an optical communication system utilizing the wavelength equalizer of the present invention. One embodiment of the optical communication system is a switched wavelength division multiplexed optical
15 communication system comprising at least one optical fiber carrying a wavelength division multiplexed signal and the present wavelength equalizer.

Further features of the invention will become more apparent from the following detailed description of specific embodiments thereof when read in conjunction with the accompanying drawings.

20 Figure 1 is a side view of a prior art mechanical anti-reflection switch modulator.

Figure 2 is a schematic illustration of a switched wavelength division multiplexed optical communication system in accordance with the present invention.

Figure 3 is an end view of an optical fiber in the wavelength equalizer of Figure 2.

25 Figure 4 is an alternate end view of an optical fiber in the wavelength equalizer of Figure 2.

Figure 5 is a schematic illustration of a second embodiment of a wavelength equalizer in accordance with the present invention.

Figure 6 is a schematic illustration of a third embodiment of a wavelength equalizer in accordance with the present invention.

30 Figure 7 is a schematic illustration of a fourth embodiment of a wavelength equalizer in accordance with the present invention.

Figure 8 is a top view of a micro-mechanical device in accordance with the present invention.

Figure 9 is a top view of a gimbal in accordance with the present invention.

Figure 10 is a perspective view of the micro-mechanical device of Figure 8 with the mirror in an out-of-plane configuration.

Figure 11 is a perspective view of an alternate micro-mechanical device in accordance with the present invention.

Figure 12 is a perspective view of the micro-mechanical device of Figure 11 in an out-of-plane configuration.

Figure 13 is a top view of a thermal actuator for use in the gimbal micro-mirror in accordance with the present invention.

Figure 14 is a side view of the thermal actuator of Figure 13.

Figure 15 is a sectional view of the thermal actuator of Figure 13.

Figure 16 is a sectional view of the thermal actuator of Figure 13.

Figure 17 is a side view of the thermal actuator of Figure 14 in an actuated position.

Figure 18 is a top view of an alternate thermal actuator including a wave guide in accordance with the present invention.

Figure 19 is a side view of the thermal actuator of Figure 18.

Figure 20 is a schematic illustration of a fifth embodiment of a wavelength equalizer in accordance with the present invention.

The present invention relates to a wavelength equalizer for an optical communication system. Although the present method and apparatus can be used in any application where it is desirable to attenuate specific wavelengths in a multiplexed signal, the present invention is especially well suited for selectively attenuating signals to compensate for path dependent losses in multiplexed optical fiber communication systems. As such, the present method and apparatus will be described in an application of a switched wavelength division multiplexed optical communication system containing a plurality of paths that each contains a unique degree of signal loss.

As used herein, "wavelength equalizer" refers to an apparatus that can selectively reduce the amplitude of any wavelength signal an arbitrary amount and not affect the

adjacent wavelengths. Although “equalizer” is a term of art that implies signal of equal strength, it is not necessarily the case that an equalizer renders the signal strength of adjacent wavelengths equal. For example, in some applications the equalizer can function to maintain differential signal strengths between adjacent wavelengths.

5 Figure 2 is a schematic illustration of a switched wavelength division multiplexed optical communication system 50 coupled to wavelength equalizer 52 in accordance with the present invention. The communication system 50 includes input optical fiber 54 capable of carrying a multiplexed signal. The optical fiber 54 has a given transmission loss, coupling loss, splitting loss and may or may not pass through any number of erbium
10 doped fiber amplifiers 56.

 The input optical fiber 54 is optically coupled to a wavelength division demultiplexer 58. The demultiplexer 58 converts the multiplexed optical signal 60 carried by the input fiber 54 into a plurality of discrete wavelengths or channels 70. As used
15 herein, “discrete wavelengths” or “channels” refers to a segment or slice of the electromagnetic spectrum. The typical size of the segment or slice for telecommunications applications at the present level of technology is about 0.5 nanometers or larger. A demultiplexer refers to a device that receives a beam consisting of multiple wavelengths and separates the beam into discrete wavelengths or channels. A multiplexer refers to a
20 device that functions in exactly the opposite manner. The multiplexer receives many optical wavelengths and converges them into one beam. Passive demultiplexers are based on prisms, diffraction gratings, arrayed wave guide grating, and spectral frequency filters. Active demultiplexers are based on a combination of passive components and tunable detectors, each detector tuned to a specific frequency.

 The discrete wavelengths 70 are each transmitted through discrete optical fibers 62
25 that are positioned to optically couple with a corresponding number of micro-mechanical mirrors 66 on a micro-mechanical device 68. In the configuration illustrated in Figure 2, substantially the entire optical signal 70 transmitted from the optical fiber 62 is reflected off the micro-mechanical mirror 66 to corresponding optical fibers 64. The micro-mirrors 66 are preferably in an in-plane configuration relative to the micro-mechanical device 68.
30 As used herein, the term “in-plane” refers to a configuration generally parallel to the surface of the substrate. As illustrated in Figure 3, optical signal 70 is substantially

reflected to the optical fiber 64. The reflected optical signal 70 passes through the multiplexer 72 where the discrete wavelengths 70 are recombined into a reconstituted multiplexed signal 78.

5 One or more of the mirrors 66 can be rotated out-of-plane relative to the micro-mechanical device 68. As used herein, the term "out-of-plane" refer to an angle of greater than zero degrees to ninety degrees relative to the surface of the substrate. The mirrors 66 can typically be moved through one or more degrees of freedom. By changing the angle of one or more of the micro-mirrors 66 relative to the micro-mechanical device 68, and hence, relative to the corresponding optical fibers 62, 64, a portion of the optical
10 signal 70 is diverted from the optical fiber 64. As used herein, "divert" means to redirect or misdirect a portion of an optical signal from an optical path, resulting in partial or total attenuation. As illustrated best in Figure 4, only a portion of the optical signal 70 reflecting from an out-of-plane mirror 66 is optically coupled with the optical fiber 64. The remainder of the optical signal 70 is diverted to the region 74 on the cladding 76 of the
15 optical fiber 64, thereby attenuating the optical signal 70 upstream from the multiplexer 72.

Typically, only certain wavelengths require attenuation. Consequently, some of the optical signals 70 are attenuated while others are not. For example, some of the micro-mirrors may be in the in-plane configuration while others are in an out-of-plane
20 configuration. The mixture of attenuated and non-attenuated optical signals 70 pass through the multiplexer 72 to form the reconstituted wavelength division multiplexed signal 78. As used herein, "reconstituted wavelength division multiplexed signal" refers to a multiplexed signal formed from a plurality of discrete wavelengths exiting from a wavelength equalizer.

25 Turning back to Figure 2, the demultiplexer 58 and the multiplexer 72 can optionally contain a series of beam splitters or coupling devices that divert a small portion of the discrete wavelengths 70 to detectors that measure the signal strength (or optical power) of the discrete wavelengths. The measured signal strength is transmitted to controller 80. Controller 80 then selectively controls the position of the mirrors 66 to
30 achieve the desired level of attenuation of the optical signal 70.

In an alternate embodiment, information relating to the intensity of the incoming or outgoing wavelengths of the optical signal can be measured upstream of the demultiplexer 58 and/or downstream of the multiplexer 72. The controller 80 can adjust the signal strength of individual wavelengths real-time in response to the monitored signal strength.

5 Consequently, the present wavelength equalizer 52 can adapt dynamically to changes in signal strength of discrete wavelengths in the switched wavelength division multiplexed optical communication system 50.

Figure 5 is a schematic illustration of a second embodiment of a wavelength equalizer 100 in accordance with the present invention. The incoming collimated

10 multiplexed optical signal 102 is directed to a diffraction grating 104. The collimated multiplexed optical signal 102 impinges upon the diffraction grating 104 so that each wavelength of light is dispersed at an angle proportional to its wavelength. The various wavelengths 106 are directed towards a plurality of discrete mirrors 108 on a micro-mechanical device 110.

15 In the nominal configuration illustrated in Figure 5, substantially all of the wavelengths 106 are reflected off the mirrors 108 directly back to the grating 104, where the wavelengths 106 are multiplexed into outgoing optical signal 112. The wavelengths 106 move along substantially the same optical path to and from the micro-mirrors 108. Minor adjustments in the angular relationship of the mirrors 108 with respect to the grating

20 104 will deflect a portion of the beams 106 and prevent the deflected portion from recombining at the grating 104 into the outgoing optical signal 112. A controller (see Figure 2) is typically used to adjust the position of the mirrors 108.

Figure 6 is a schematic illustration of a third embodiment of a wavelength equalizer 120 in accordance with the present invention. The incoming collimated

25 multiplexed optical signal 122 strikes a grating 124 which disperses each wavelength of light at an angle proportional to its wavelength. The various wavelengths 126 are directed to impinge on mirrors 128 of micro-mechanical device 130. The wavelengths 126 reflect off the mirrors 128 and are directed to a second grating 132 that combines the wavelengths 126 into outgoing optical signal 134. The wavelengths 126 travel different optical paths

30 before and after reflecting off the micro-mirrors 128. Again, minor adjustments in the angular relationship of the mirrors 128 with respect to the grating 132 will deflect a

portion of the beams 126 and prevent the deflected portion from recombining at the grating 132 into the outgoing optical signal 134.

Figure 7 illustrates a fourth embodiment of a alternate wavelength equalizer 140 in accordance with the present invention. Prism 142 divides incoming collimated multiplexed optical signal 144 into discrete constituent wavelengths 146. Beam splitter 148 is optionally located downstream of the prism 142 to redirect a small portion of the wavelengths 146 to detectors 151 in controller 150. The wavelengths 146 strike mirrors 152 as discussed above and are reflected to prism 154 that combines them into outgoing signal 156.

Beam splitter 158 may optionally be located downstream of prism 154. The beam splitter diverts a small portion of the outgoing optical signal 156 to prism 160 that separates the optical signal into its constituent wavelengths. These wavelengths are then directed to detectors 151 in the controller 150 to measure the intensity of each wavelength in the outgoing optical signal 156. The controller 150 can use the intensity measured from the optical signals collected at the beam splitters 148 and 158 to control the position of the mirrors 152.

As used herein, "micro-mechanical device" refers to micrometer-sized mechanical, opto-mechanical, electro-mechanical, or opto-electro-mechanical device constructed on a substrate. Various technologies for fabricating micro-mechanical devices are available, such as for example the Multi-User MEMS Processes (MUMPs) from Cronos Integrated Microsystems located at Research Triangle Park, North Carolina. One description of the assembly procedure is described in "MUMPs Design Handbook," revision 5.0 (2000) available from Cronos Integrated Microsystems.

Polysilicon surface micromachining adapts planar fabrication process steps known to the integrated circuit (IC) industry to manufacture micro-electro-mechanical or micro-mechanical devices. The standard building-block processes for polysilicon surface micromachining are deposition and photolithographic patterning of alternate layers of low-stress polycrystalline silicon (also referred to a polysilicon) and a sacrificial material (for example, silicon dioxide or a silicate glass). Vias etched through the sacrificial layers at predetermined locations provide anchor points to a substrate and mechanical and electrical interconnections between the polysilicon layers. Functional elements of the device are

built up layer by layer using a series of deposition and patterning process steps. After the device structure is completed, it can be released for movement by removing the sacrificial material using a selective etchant such as hydrofluoric acid (HF) which does not substantially attack the polysilicon layers.

5 The result is a construction system generally consisting of a first layer of polysilicon which provides electrical interconnections and/or a voltage reference plane, and additional layers of mechanical polysilicon which can be used to form functional elements ranging from simple cantilevered beams to complex electro-mechanical systems. The micro-mirror is located in-plane with the substrate. Since the entire process is based
10 on standard IC fabrication technology, a large number of fully assembled devices can be batch-fabricated on a silicon substrate without any need for piece-part assembly.

 Figure 8 is a top view of a micro-mechanical device 220 including a gimbaled micro-mirror 221 and one or more thermal actuators 252A-252L (referred to collectively as "252") suitable for use in the present wavelength equalizer. Mirror 222 on the gimbaled
15 micro-mirror 221 is formed so that surface 224 is highly reflective. The mirror 222 is retained to substrate 226 by a plurality of torsional hinges or gimbals 228A-228D (referred to collectively as "228"). As used herein, "gimbal" refers to a micro-mechanical device that mechanically couples a mirror or other structure to a substrate of a substrate while permitting movement through at least two degrees of freedom (typically pitch and roll)
20 relative to the surface of the substrate.

 In the illustrated embodiment, the mirror 222 is generally square and the gimbals 228 are located along the four sides thereof. The shape of the mirror, the number of gimbals and the location of gimbals can vary with the application of the gimbaled micro-mirror 221. For example, the gimbals 228 can be located at the corners of the gimbaled
25 micro-mirror 221. The micro-mirrors 221 of the present invention are preferably shaped to permit a closely packed array, such as angular shapes including triangular, rectangular or have five or more sides, hexagonal, octagonal and the like. Alternatively, the gimbaled micro-mirror 221 may also be circular.

 As best illustrated in Figure 9, the gimbals 228 each includes a pair of first arms
30 230, 232 cantilevered from the mirror 222 to members 234, 236, respectively. Second arms 238, 240 are cantilevered from the members 234, 236 to the anchor 242. Although

the arms 232, 240 and 230, 238 are generally perpendicular to the mirror 222 and generally parallel in the illustrated embodiment, this configuration is not required. The arms 230, 232, 238, 240 can be at an angle with respect to the mirror 222 and/or with respect to each other. Additionally, the arms 230, 232, 238, 240 can be curvilinear in shape. In one
5 embodiment, the gimbals 228 suspend the mirror 222 over the surface of the substrate 226. In an alternate embodiment, the mirror 222 rests on the surface of the substrate 226, but is moveably retained to the substrate 226 by the gimbals 228.

Pads 244 are optionally located under the members 234, 236 to support the arms 230, 232, 238, 240. The pads 244 can also serve as limits or end-stops on the deflection of
10 the arms 230, 232, 238, 240 and/or the mirror 222. The resistance and stiffness of the gimbals 228 during operation can be modified by increasing or decreasing the number, length and cross-sectional area of arms and a variety of other factors. For example, the anchor 242 can be moved closer to the members 234, 236. In an alternate embodiment, the arms 232, 240 can be eliminated.

Turning back to the illustrated embodiment of Figure 8, a plurality of supports or outriggers 246 extend from a perimeter 248 of the mirror 222. In one embodiment, the supports 246 include pads 250 that are adapted to engage with the surface of the substrate 226 when the mirror 222 is in a neutral position. In another embodiment, the pads 250 are located on the surface of the substrate 226. In another embodiment, the pads 250 also
15 serve as limits or end-stops for movement of the mirror 222. In another embodiment, the pads 250 maintain the mirror 222 in a fixed and repeatable relationship relative to the substrate 226 when in the neutral position.

As used herein, "neutral position" refers to the relationship of the mirror relative to the surface of the substrate when the thermal actuators are in an unactivated position. In
25 one embodiment, outriggers 246 rest on the pads 250 in the neutral position. The neutral position can be also the in-plane configuration or the out-of-plane configuration.

The plurality of thermal actuators 252 are located around the perimeter of the mirror 222. The number, location and configuration of the thermal actuators 252 can vary with the application. In the illustrated embodiment, the thermal actuators 252 are located
30 at the corners of the square mirror 222.

Free ends 253 of the thermal actuators 252 are positioned under supports 257 located at the corners of the mirror 222, but are not attached to the supports 257. The mirror 222 is attached to the substrate 226 by the gimbals 228 independent of the actuators 252. When any of the thermal actuators 252 are activated, one or more of the free ends 253 engage with the adjacent support 257 and raise the mirror 222 out-of-plane (see Figure 10). When the thermal actuators 252 are in the unactivated position, the mirror 222 returns to a neutral position (see Figure 8). The mirror 222 substantially returns to a neutral position when actuators 252 are in the unactivated position due to torsional forces of the gimbal. In one embodiment, the mirror 222 can be assisted back to the neutral position by an electrostatic force.

Each of the thermal actuators 252 includes one or more anchors 254, 256. Electrical trace 258 connects anchor 254 to grounding trace 260. Electrical trace 262 connects anchor 256 to a source of current 264. As illustrated in Figure 10, by selectively applying current to some of the thermal actuators 252, the mirror 222 can be moved out-of-plane in pitch and/or roll, or a combination thereof. As the thermal actuators 252A, 252B, 252C move to the out-of-plane configuration, the free ends 253A-253C engage with the support 257 to raise the mirror 222.

In some embodiments, the free ends 253A-253C move through an arc in the activated position so that there is some lateral displacement (parallel to the surface of the substrate) of the free ends 253 relative to the support 257. Consequently, the free ends 253 may slide along the lower surface of the support 257 (or the mirror 222) as the mirror 222 is raised. Some or all of the gimbal 228 are deformed to compensate for the displacement of the mirror 222. Since the free ends 253A-253C are not attached to the supports 257, the mirror 222 can be moved with less force and greater accuracy.

Figure 11 is a perspective view of a second embodiment of a micro-mechanical device 290 in accordance with the present invention. A pair of thermal actuators 300, 302 are mechanically coupled to a micro-mirror 304 formed on substrate 306. The mirror 304 is attached to the substrate 306 by one or more flexures or hinges 308 formed at a first end 310. Flexures used on thermal actuators are suitable for this purpose. The mirror 304 is otherwise not attached to the substrate. The hinges 308 provide the micro-mirror with at least one degree of freedom.

The hinges 308 nominally lie flat on the surface of the substrate 306, but can be rotated out-of-plane. A variety of hinged-plates of differing size, shape, and locations on a substrate can be used. The hinge 308 can be a torsional hinge or a flexure that provides a restoring force to move the mirror back to the in-plane position (see Figure 11).
5 Alternatively, the mirror 304 can be restored to the in-plane configuration by gravity, a micro-mechanical spring structure formed on the substrate 306, an electrostatic force or a variety of other mechanisms. Forming such hinged plates is disclosed in Pister et al., "Microfabricated Hinges", vol. 33, Sensors and Actuators A, pp. 249-56, 1992 and U.S. Pat. Nos. 5,923,798 and 5,912,094.

10 A shaft 312 is attached to the mirror 304 near the first end 310. The shaft 312 may be supported by a plurality of anchors 314 that permit the shaft 312 to rotate within certain limits. One or more flip levers 316 are anchored to the shaft 312. The free ends 318, 320 of the thermal actuator 300, 302, respectively, are positioned underneath the flip levers 316. The free ends 318, 320 are preferably located close to the shaft 312 so as to obtain
15 the maximum mechanical advantage.

Figure 12 is a perspective view of the thermal actuators 300, 302 of Figure 11 in the activated configuration. As current is applied to the thermal actuators 300, 302, the lifting force discussed above raises the flip levers 316, which in turn raise the micro-mirror 304 to an out-of-plane position. When the current is removed, the micro-mirror 304
20 returns to a position substantially in-plane as illustrated in Figure 11. Although Figures 11 and 12 illustrate a mirror with two thermal actuators, a single thermal actuator or multiple thermal actuators may be used.

The micro-mechanical devices of the present invention can utilize a variety of actuators to position the mirrors, including electrostatic, piezoelectric, thermal and
25 magnetic actuators. For example, U.S. Pat. No. 6,028,689 (Michalicek et al.) discloses a multi-motion micro-mirror manipulated by electrostatic potential. In one embodiment, the mirrors are positioned by thermal actuators. The micrometer sized thermal actuators are capable of repeatable and rapid moving the micro-mirror out-of-plane to accurately and repeatably steer a beam of light.

30 Figures 13 through 17 illustrate an exemplary embodiment of a thermal actuator 450 suitable for use in the present invention. As used herein, "thermal actuator" refers to a

thermally activated micro-mechanical device capable of repeatably moving an optical device, such as the present micro-mirrors, between an in-plane position and an out-of-plane position. In the exemplary embodiment, the thermal actuator 450 is designed to provided controlled bending. As used herein, "controlled bending" refers to bending that
5 occurs primarily at a discrete location, rather than being distributed along the beams of the thermal actuator.

The thermal actuator 450 is oriented in-plane on a surface of a substrate 452 typically comprising a silicon wafer 454 with a layer of silicon nitride 456 deposited thereon. The actuator 450 includes a first layer 460 of polysilicon located on the layer of
10 silicon nitride 456. As best seen in Figure 16, the first layer 460 comprises a bump that forms the reinforcing member 485 in the cold beam 484. A second layer of polysilicon 462 is configured to have first and second anchors 464, 466 and a pair of beams 468, 470 arranged in a cantilever fashion from the anchors 464, 466 respectively.

In the embodiment illustrated in Figure 13, the anchors 464, 466 include electrical
15 contacts 476, 478 formed on the substrate 452 adapted to carry electric current to the beams 468, 470. The traces 476, 478 typically extend to the edge of the substrate 452. Alternatively, a wide variety of electric contact devices and/or packaging methods such as a ball grid array (BGA), land grid array (LGA), plastic leaded chip carrier (PLCC), pin grid array (PGA), edge card, small outline integrated circuit (SOIC), dual in-line package
20 (DIP), quad flat package (QFP), leadless chip carrier (LCC), chip scale package (CSP) can be used to deliver electric current to the beams 468, 470.

The beams 468, 470 are electrically and mechanically coupled at their respective free ends 471, 473 by member 472 to form an electric circuit. In an alternate embodiment, beams 468, 470 are electrically coupled to grounding tab 477. The grounding tab 477
25 electrically couples the beams 468, 470 to contact 479 on the substrate 452 in both the unactivated configuration (see Figure 14) and the activated configuration (see Figure 17). The grounding tab 477 can be a flexible member or a spring member that is adapted to maintain contact with the contact 479. A grounding tab can be used with any of the embodiments disclosed herein.

30 The beams 468, 470 are physically separated from the first layer 460 so that the member 472 is located above the substrate 452. One or more dimples 474 may optionally

be formed in the member 472 to support the beams 468, 470 above the substrate 452. In an alternate embodiment, the dimples or bumps 474 can be formed on the substrate 452. In an unactivated configuration illustrated in Figure 14, the beams 468, 470 are generally parallel to the surface of the substrate 452. As used herein, the “unactivated configuration” refers to a condition in which substantially no current is passed through the circuit formed by the beam 468, the member 472 and the beam 470.

A third layer 480 of polysilicon is configured with an anchor 482 attached to the substrate 452 near the anchor 464, 466. The third layer 480 forms upper beam 484 cantilevered from the anchor 482 with a free end 483 mechanically coupled to the member 472 above the beams 468, 470. In some embodiments, reinforcing member 485 is formed in the upper beam 484 along at least a portion of its length and flexure 487 is optionally formed in the upper beam 484 near the anchor 482. In one embodiment, a metal layer is optionally applied to the upper beam 484.

As used herein, “reinforcing member” refers to one or more ridges, bumps, grooves or other structural features that increase resistance to bending. The reinforcing members are preferably formed during the MUMPs process so that it is integrally formed with the upper beam 484. In the illustrated embodiment, the reinforcing member 485 is a curvilinear ridge (see Figure 16) extending along a portion of the upper beam 484, although it could be rectangular, square, triangular or a variety of other shapes. Additionally, the reinforcing member 485 can be located in the center of the upper beam 484 or along the edges thereof. Multiple reinforcing members may also be used.

As used herein, “flexure” refers to a recess, depression, hole, slot, cut-out, location of narrowed, thinned or weakened material, alternate material or other structural features or material change that provides controlled bending in a particular location. Alternate materials suitable for use as a flexure include polysilicon, metal or polymeric material. As best illustrated in Figures 13 and 15, the flexure 487 is a recess 489. The recess 489 comprises the weakest section of the upper beam 484, and hence, the location most likely to bend during actuation of the thermal actuator 450.

The rigidity of the upper beam 484 relative to the rigidity of the flexure 487 determines to a large extent the magnitude (location and direction) of the controlled bending of the thermal actuator 450. In one embodiment, the reinforcing member 485 is

used in combination with the flexure 487. In another embodiment, the reinforcing member 485 extends along a portion of the upper beam 484, but no flexure is used. The portion of the upper beam 484 without the reinforcing member 485 is the location of controlled bending. In yet another alternate embodiment, the flexure 487 is formed in the beam 484 without the reinforcing member 485 such that the flexure 487 is the location of controlled bending. The thermal actuator 450 can also be use without either the reinforcing member 485 or the flexure 487.

A via 488 is formed at the member 472 and/or free end 483 to mechanically couple the free end 483 of the upper beam 484 to the member 472. Other structures may be used to mechanically couple the upper beam 484 to the member 472. The upper beam 484 is generally parallel to surface of the substrate 452 in the unactivated configuration.

Figure 17 is a side sectional view of the thermal actuator 450 of Figures 13-16 in an out-of-plane or activated configuration. The "activated configuration" refers to applying electrical current to one or more of the beams. In the illustrated embodiment, electric current is applied to the circuit formed by the beam 468, the member 472, and the beam 470 (see Figure 13). The beams 468, 470 are the "hot arms" and the beam 484 is the cold arm. As used herein, "hot arm" or "hot arms" refer to beams or members that have a higher current density than the cold arm(s) when a voltage is applied. "Cold arm" or "cold arms" refer to beams or members that have a lower current density than the hot arm(s) when a voltage is applied. In some embodiments, the cold arm(s) has a current density of zero. Consequently, the hot arms have greater thermal expansion than the cold arms.

The electric current heats the hot arms 468, 470 and causes them to increase in length in the direction 490. Expansion of the beams 468, 470 causes the free ends 471, 473 of the thermal actuator 450 to move in an upward arc 492, generating lifting force 494 and displacement 495. The cold arm 484, however, is fixed at the anchor 482 and electrically isolated so that the current entirely or substantially passes through the circuit formed by the hot arms 468, 470 and the member 472.

Due to the height difference between the cold arm 484 and the hot arms 468, 470, a moment is exerted on the cold arm 484 near the anchor 482. The cold arm 484 bends near the flexure 487, resulting in greater displacement near the free end 483 than would occur without the flexure 487. The hot arms 468, 470 also bend easily, offering little resistance

to the motion 492 of the cold arm 484. The reinforcing member 485 resists bending along the cold arm 484 that would normally occur near the member 472 when a load is placed at the free end 483. In the illustrated embodiment, the displacement 495 can be from 0.5 micrometers to 4 micrometers. When the current is terminated, the thermal actuator 450
5 returns to its original, unactivated configuration illustrated in Figure 14.

In an alternate embodiment, the anchor 482 and the cold arm 484 are electrically coupled to the member 472. At least a portion of the current flowing through the hot arms 468, 470 flows along the cold arm 484 to the anchor 482. It is also possible that all of the current flowing through the hot arms 468, 470 exits the thermal actuator 450 through the
10 cold arm 484. The material and/or geometry of the cold arm 484 is adapted to have a lower current density than the hot arms 468, 470, even when the same voltage is applied. In one embodiment, the cold arm 484 is formed from a material with a coefficient of linear thermal expansion less than the coefficient of linear thermal expansion of the hot arms 468, 470. In yet another embodiment, the cold arm 484 is provided with a lower electrical
15 resistivity by having a larger cross sectional area. In another embodiment, a conductive layer is provided on the cold arm 484. Suitable conductive materials include metals such as aluminum, copper, tungsten, gold, or silver, semiconductors, and doped organic conductive polymers such as polyacetylene, polyaniline, polypyrrole, polythiophene, polyEDOT and derivatives or combinations thereof. Consequently, the net expansion of
20 the hot arms 468, 470 is greater than the expansion of the cold arm 484.

In another alternate embodiment, all or a portion of the current flowing through the hot arms 468, 470 flows through grounding tab 477 to the contact 479 on the substrate 452. The grounding tab 477 maintains electrical and physical contact with the contact 479 as the thermal actuator 450 moves from the unactivated position to the activated position
25 illustrated in Figure 17.

Alternate thermal actuators are disclosed in commonly assigned U.S. Patent Application No. 09/659,572, entitled "Direct Acting Vertical Thermal Actuator", filed September 12, 2000; U.S. Patent Application No. 09/659,798, entitled "Direct Acting Vertical Thermal Actuator with Controlled Bending", filed September 12, 2000; and U.S.
30 Patent Application No. 09/659,282, entitled "Combination Horizontal and Vertical Thermal Actuator", filed September 12, 2000.

Figures 18 and 19 illustrates an alternate thermal actuator 500 suitable for use in a wavelength equalizer in accordance with the present invention. A thermal actuator 500 generally as illustrated in Figures 13-17 includes a wave guide 502 attached to the cold arm 504. The wave guide 502 can be formed as part of the fabrication process or added as a separate component. The wave guide 502 is typically an optical fiber. The wave guide 502 can be effectively located on the cold arm 504 since it experiences little or no thermal expansion. The cold arm 504 is preferably electrically isolated from the hot arms 506, 508.

As best illustrated in Figure 19, when the thermal actuator 500 is in the deactivated or in-plane configuration, the wave guide 502 is positioned to optically coupled with an adjacent wave guide 510 (see Figure 3). In the activated or out-of-plane configuration, the wave guide 502 can be diverted from the adjacent wave guide 510 (see Figure 4). By varying the current applied to the thermal actuator 500, a discrete wavelength signal 512 can be attenuated as required.

Figure 20 illustrates a fifth embodiment of an alternate wavelength equalizer 520 utilizing the thermal actuator generally as illustrated in Figures 18 and 19. Input optical fibers 522 carries a multiplexed signal 526. The input optical fibers 522 is optically coupled to a wavelength division demultiplexer 524. The demultiplexer 524 converts the multiplexed optical signal 526 carried by the input fiber 522 into a plurality of discrete wavelengths or channels 528. The discrete wavelengths 528 are each transmitted through discrete optical fibers 530, each mounted on thermal actuators 532.

When the thermal actuators 532 are in the nominal configuration illustrated in Figure 19, substantially the entire optical signal 528 is transmitted from the optical fibers 530 to corresponding optical fibers 534. In the nominal configuration, the thermal actuators 532 are preferably in an in-plane, unactivated configuration. The optical fibers 534 are coupled to a multiplexer 536 that combines the discrete wavelengths 528 into outgoing signal 538.

Current can be applied to one or more of the thermal actuators 532 so that the optical fibers 530 and 534 are misaligned, resulting in partial or complete attenuation of the signal 528 (see Figure 4). In one embodiment, controller 540 monitors the signal

strength upstream and/or downstream of the optical fibers 530, 534 and controls the position of the thermal actuators 532 to equalize the signal strength.

Although specific embodiments of this invention have been shown and described herein, it is to be understood that these embodiments are merely illustrative of the many possible specific arrangements that can be devised in application of the principles of the invention. Numerous and varied other arrangements can be devised in accordance with these principles by those of ordinary skill in the art without departing from the scope and spirit of the invention. For example, any of the flexures, reinforcing structures, anchor locations and beam configurations disclosed herein can be combined to produce numerous thermal actuators.

What is claimed is:

1. A wavelength equalizer comprising:
 - a demultiplexer adapted to separate the wavelength division multiplexed
5 signal into a plurality of discrete wavelength signals and to direct each of the discrete wavelength signals along a plurality of first optical paths;
 - a micro-mechanical device comprising at least one micro-mirror optically coupled with each of the first optical paths;
 - a plurality of second optical paths positioned to receive the discrete
10 wavelength signals reflected from the respective micro-mirrors;
 - at least one actuator mechanically coupled with each of the micro-mirrors, the actuators being adapted to selectively displace one or more of the micro-mirrors to divert at least a portion of the discrete wavelength away from the corresponding second optical paths; and
 - 15 a multiplexer adapted to combine the discrete wavelength signals in the plurality of second optical paths into a reconstituted wavelength division multiplexed signal.
2. The apparatus of claim 1 wherein the orientation of the micro-mirror
20 determines a signal strength of the discrete wavelength signal reflected to the corresponding second optical path.
3. The apparatus of claim 1 wherein the first optical paths comprise the
25 second optical paths.
4. The apparatus of claim 1 comprising a plurality of signal strength detectors adapted to detect the optical signal strength of the discrete wavelength signals.
5. The apparatus of claim 1 comprising:
30 a beam splitter located along a plurality of the first optical paths; and

signal strength detectors optically coupled to the beam splitter to detect the signal strength of the discrete wavelength signals.

6. The apparatus of claim 1 comprising a controller operatively coupled to the actuators.

5

7. The apparatus of claim 1 comprising:

a plurality of signal strength detectors adapted to detect the signal strength of the discrete wavelength signals; and

10 a controller adapted to monitor the signal strength of the discrete wavelengths measured by the signal strength detectors and to activate the actuators to selectively attenuate one or more of the discrete wavelength signals in response to a monitored signal strength.

15 8. The apparatus of claim 1 wherein the micro-mirrors and the actuators are constructed on a surface of a substrate.

9. The apparatus of claim 8 wherein each of the micro-mirrors are attached to the surface of the substrate by at least one hinge.

20 10. The apparatus of claim 8 wherein each of the micro-mirrors are attached to the surface of the substrate by at least one gimbal.

25 11. The apparatus of claim 8 wherein each of the micro-mirrors are adapted to move through at least one degree of freedom.

12. The apparatus of claim 1 wherein the actuators comprise thermal actuators.

30 13. The apparatus of claim 12 wherein the thermal actuators comprise:
at least one hot arm having a first end anchored to the surface and a free end located above the surface;

a cold arm having a first end anchored to the surface and a free end, the cold arm being located above the hot arm relative to the surface; and

a member mechanically and electrically coupling the free ends of the hot and cold arms, the member being positioned to engage with the mirror when current is applied to at least the hot arm.

14. The apparatus of claim 12 wherein the thermal actuator comprises at least one flexure adapted to provide controlled bending.

15. The apparatus of claim 12 wherein the thermal actuator comprises at least one reinforcing member.

16. The apparatus of claim 1 wherein a micro-mirror reflects substantially all of the discrete wavelength signal from one of the first optical paths to the corresponding second optical path when the actuator is in an unactivated configuration.

17. The apparatus of claim 1 wherein a micro-mirrors reflects only a portion of the discrete wavelength signal from one of the first optical paths to the corresponding second optical paths when the actuator is in an activated configuration.

18. The apparatus of claim 1 wherein a micro-mirror reflects substantially none of the discrete wavelength signal from one of the first optical paths to the corresponding second optical path when the actuator is in an activated configuration.

19. An optical communication system comprising the wavelength equalizer of claim 1.

20. A wavelength equalizer comprising:
a demultiplexer adapted to separate the wavelength division multiplexed signal into a plurality of discrete wavelength signals and to direct each of the discrete wavelength signals along a corresponding plurality of first optical paths;

a plurality of second optical paths positioned to receive the discrete wavelength signals;

5 a micro-mechanical device comprising a thermal actuator adapted to selectively divert at least a portion of the discrete wavelength from one or more of the first optical paths away from the corresponding second optical paths; and

a multiplexer adapted to combine the discrete wavelength signals in the plurality of second optical paths into a reconstituted wavelength division multiplexed signal.

10 21. The apparatus of claim 20 wherein the micro-mechanical device comprises a plurality of micro-mirrors mechanically coupled to a plurality of thermal actuators.

22. The apparatus of claim 20 wherein the plurality of first optical paths each extend along a surface on a corresponding thermal actuator.

15 23. The apparatus of claim 22 wherein the second optical paths are optically aligned with each of the corresponding first optical paths, respectively, when the thermal actuators are in an unactivated condition.

20 24. The apparatus of claim 22 wherein the first optical paths are optically diverted from each of the corresponding first optical paths, respectively, when the thermal actuators are in an activated condition.

25 25. A switched wavelength division multiplexed optical communication system comprising:

at least one optical fiber carrying a wavelength division multiplexed signal;
a wavelength equalizer comprising;
a demultiplexer adapted to separate the wavelength division multiplexed signal into a plurality of discrete wavelength signals and to direct each of the discrete
30 wavelength signals along a corresponding plurality of first optical paths;

a micro-mechanical device comprising at least one micro-mirror optically coupled with each of the first optical paths;

a plurality of second optical paths positioned to receive the discrete wavelength signals reflected from the respective micro-mirrors;

5 at least one actuator mechanically coupled with each of the micro-mirrors, the actuators being adapted to selectively displace one or more of the micro-mirrors to divert at least a portion of the discrete wavelength away from one or more of the second optical paths; and

10 a multiplexer adapted to combine the discrete wavelength signals in the plurality of second optical paths into a reconstituted wavelength division multiplexed signal.

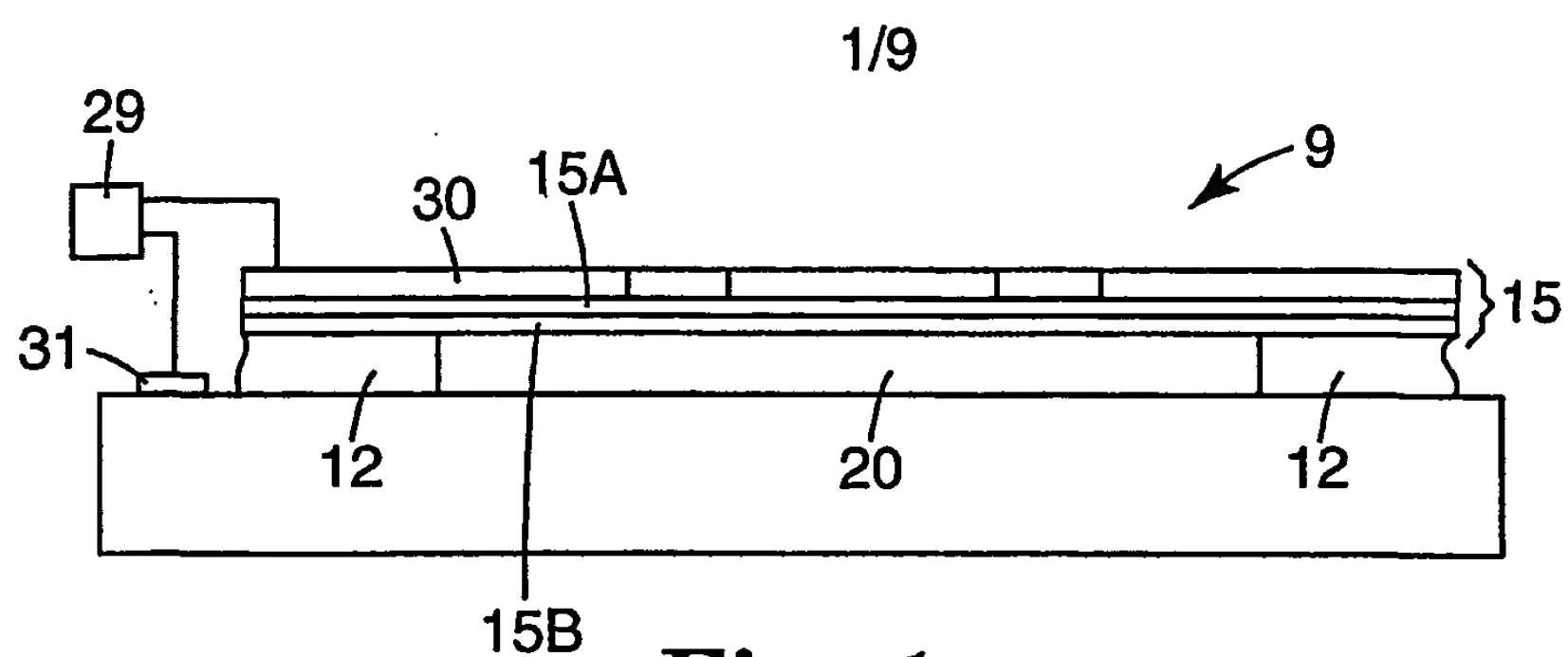


Fig. 1
PRIOR ART

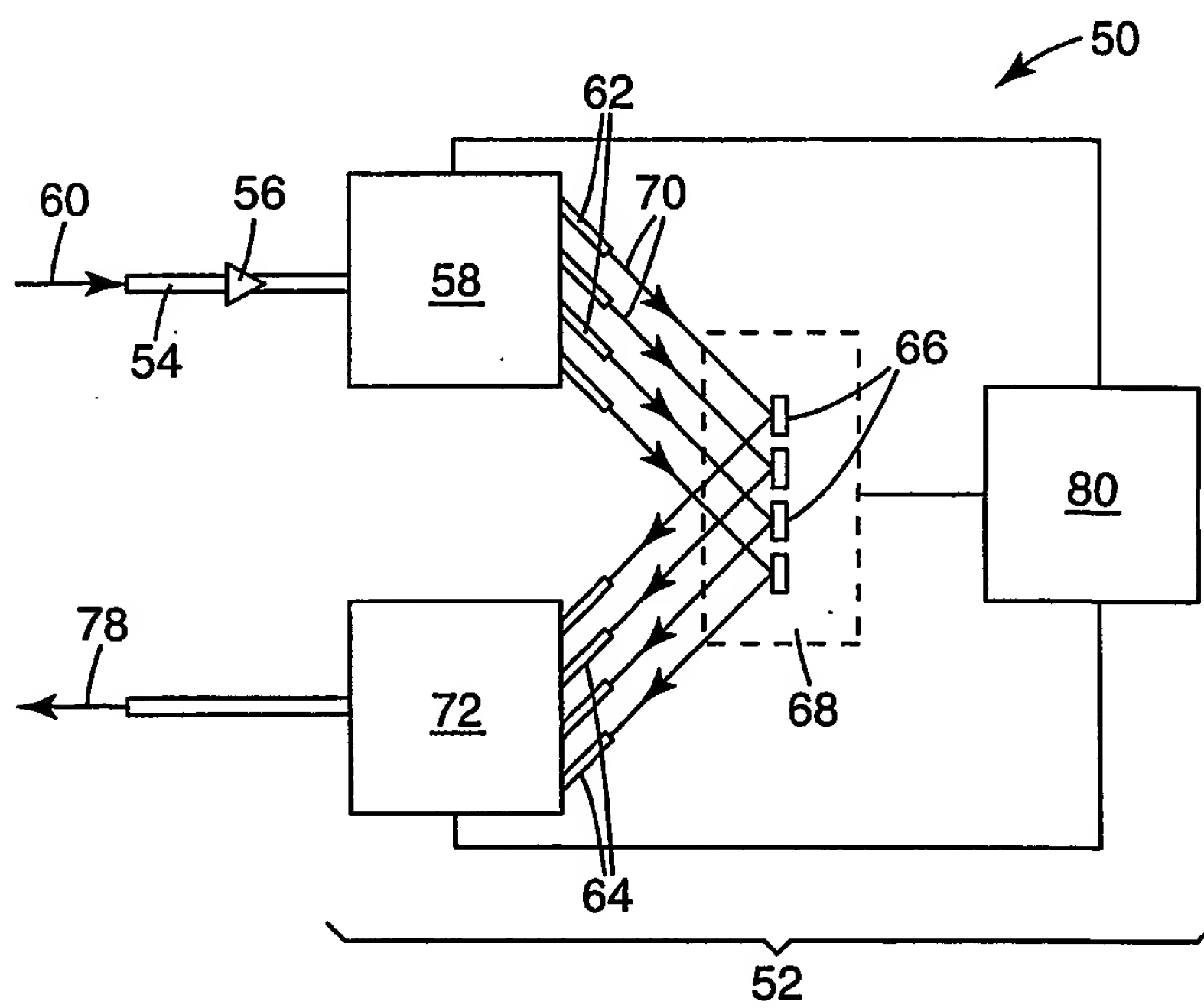


Fig. 2

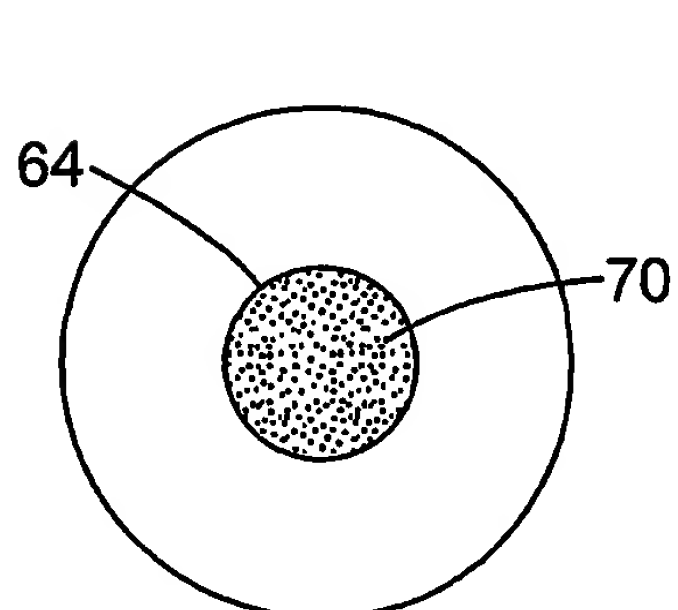


Fig. 3

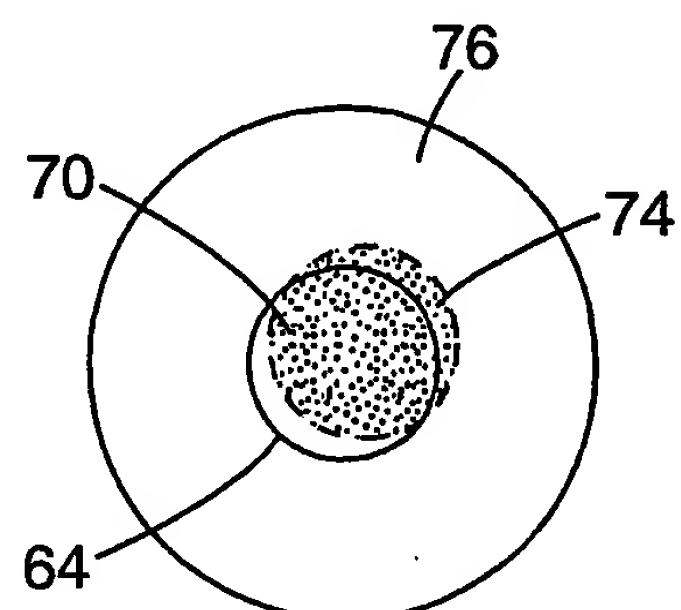
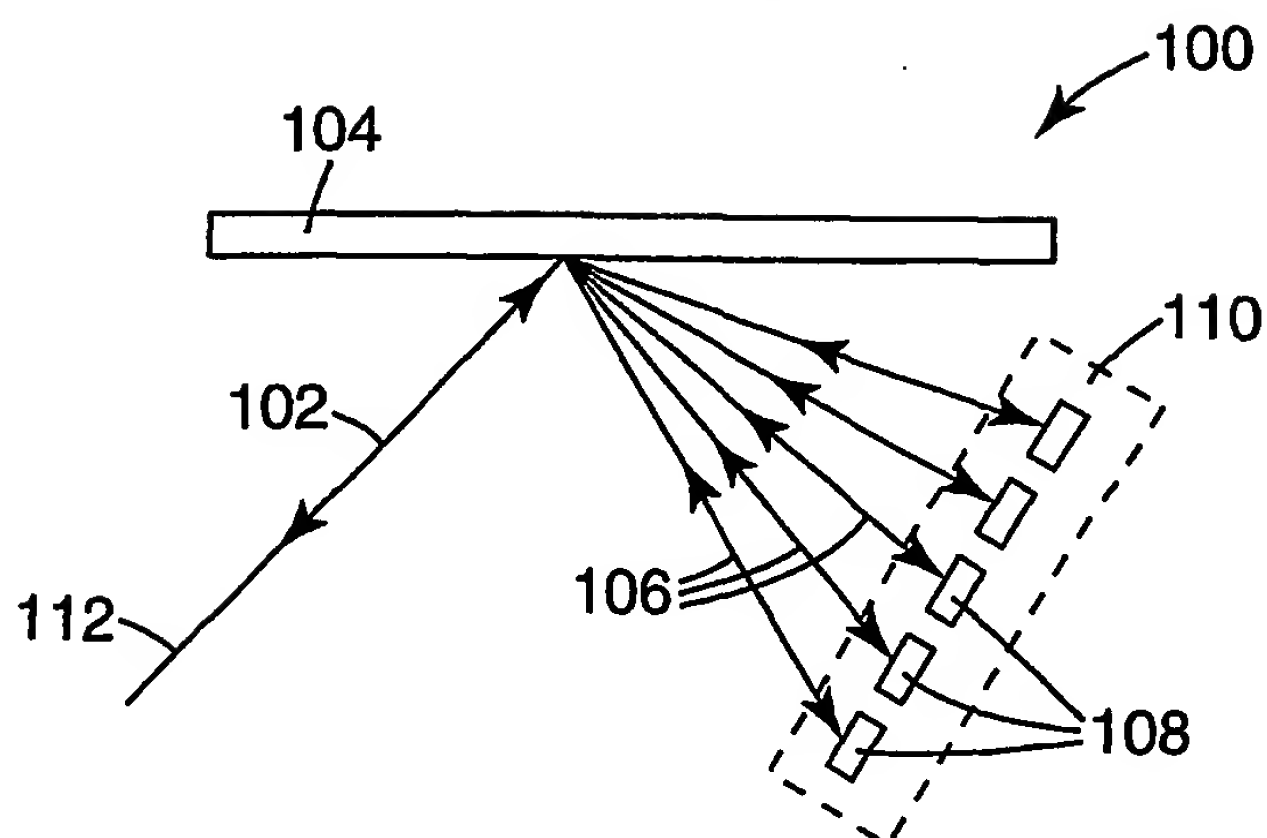
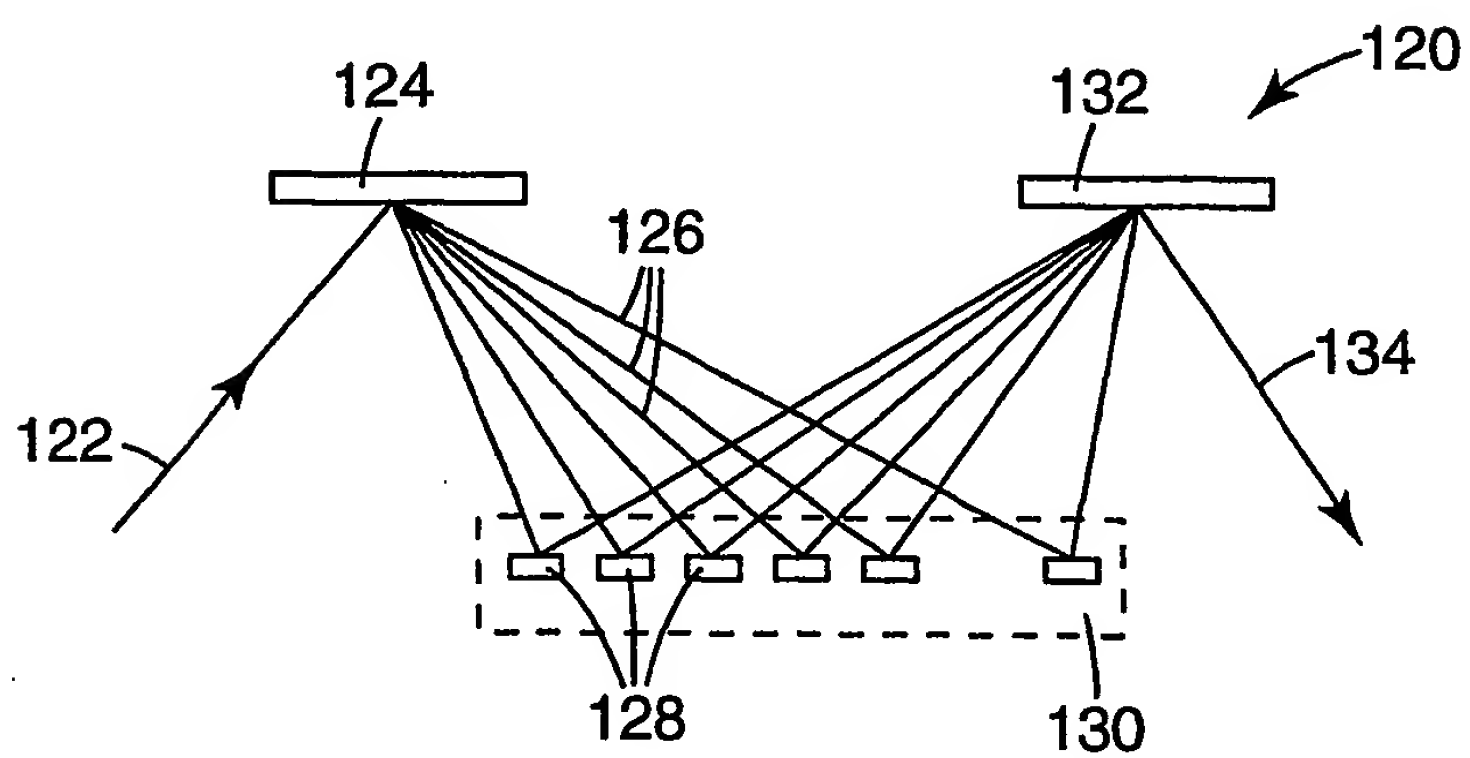
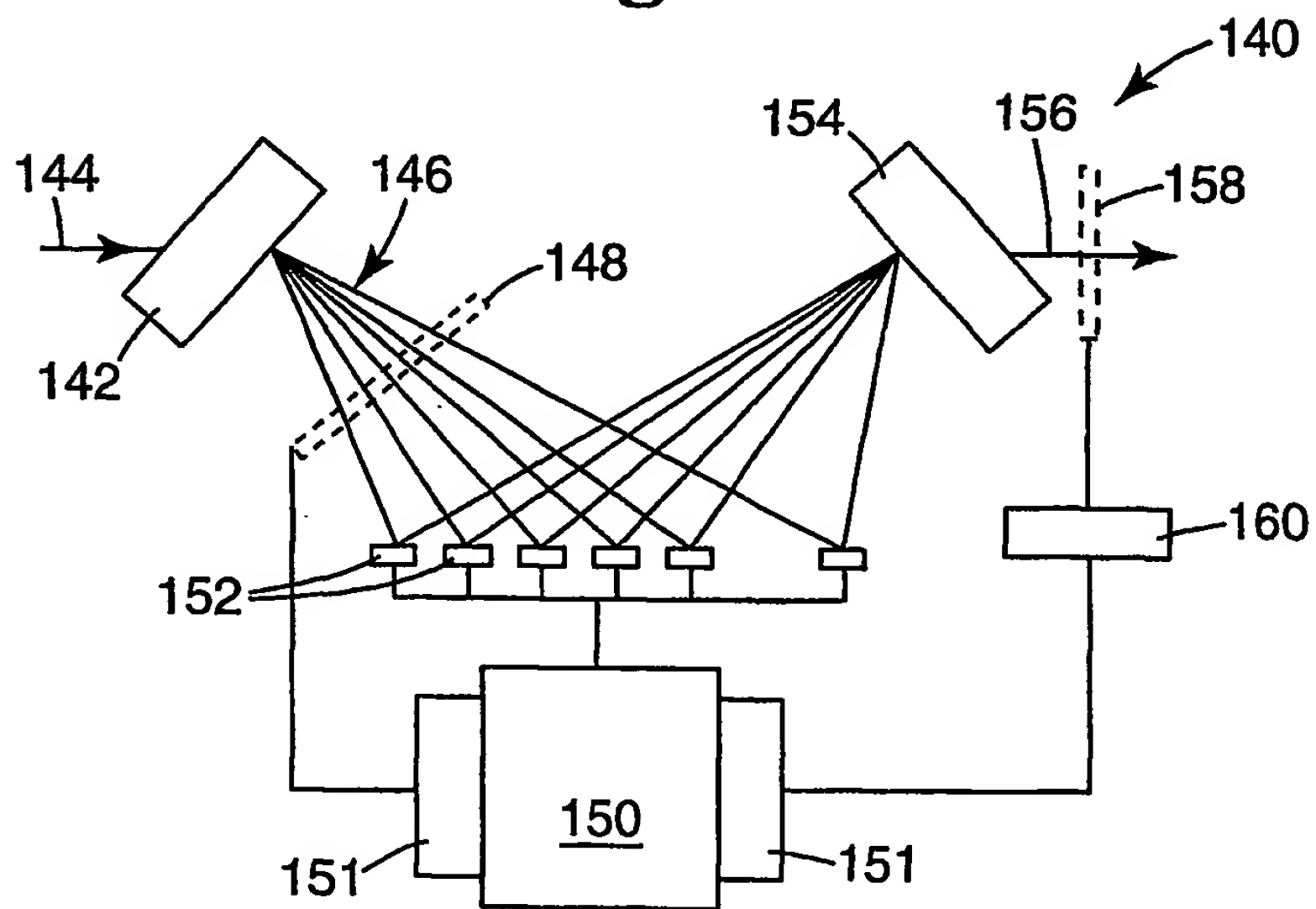
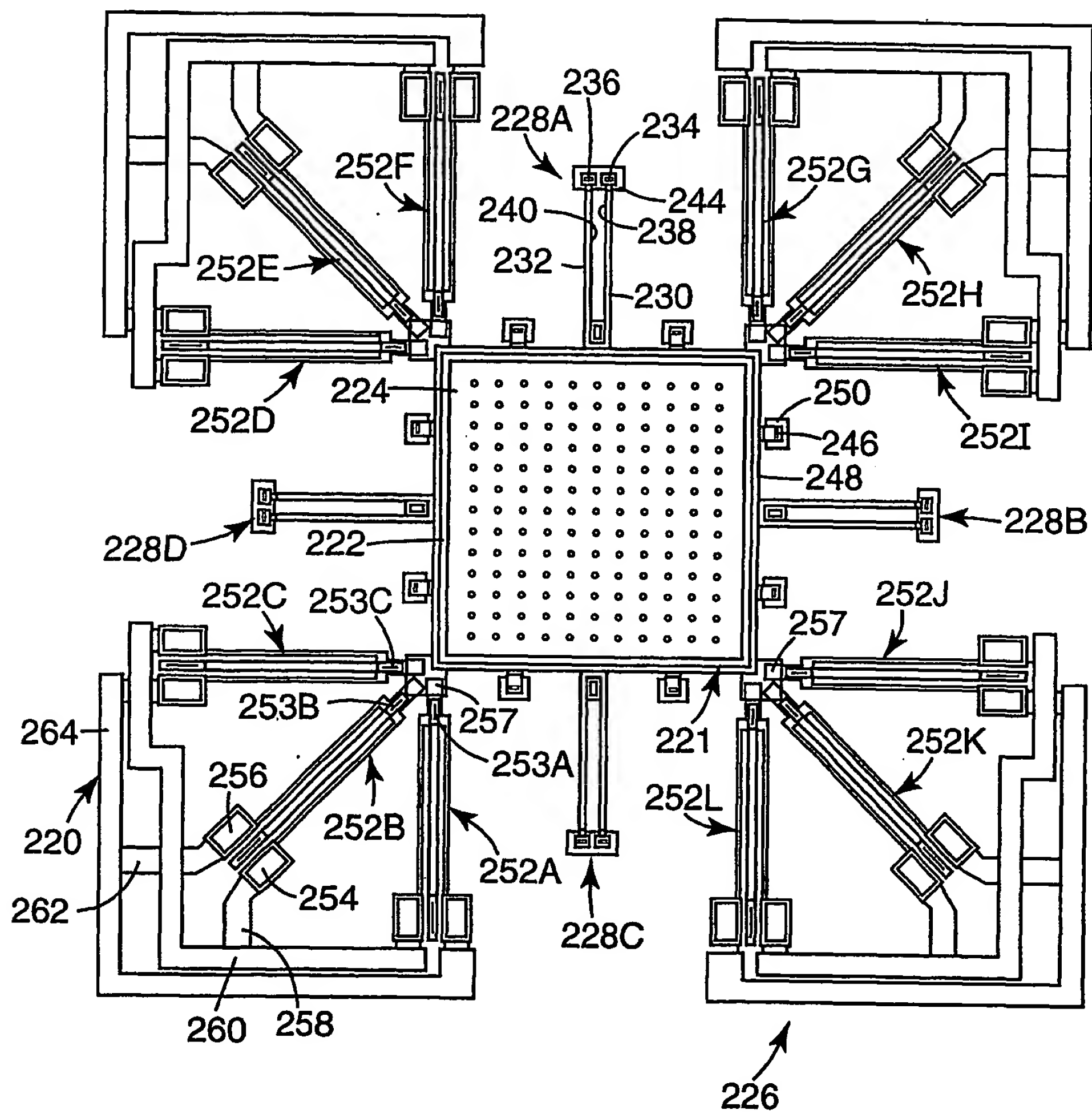


Fig. 4

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**Fig. 5****Fig. 6****Fig. 7**

**Fig. 8**

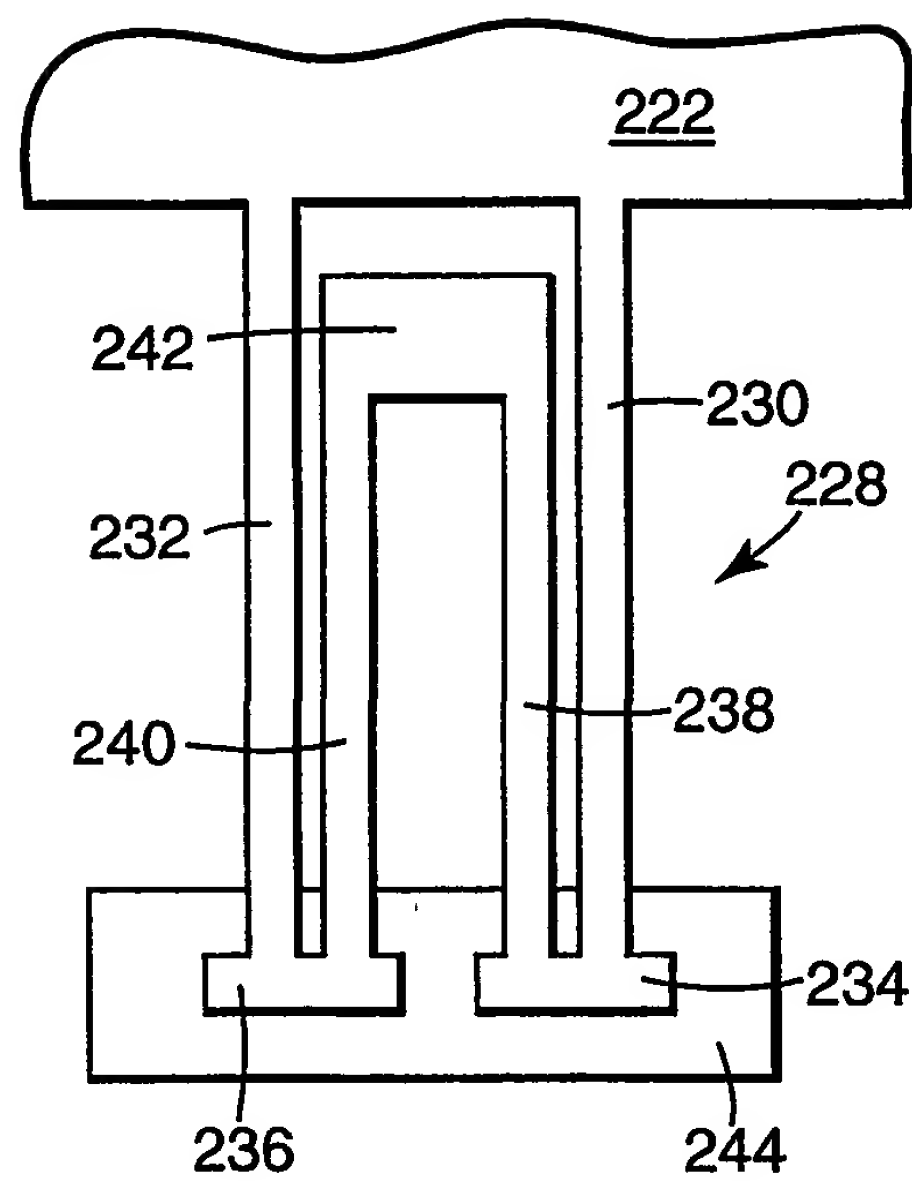


Fig. 9

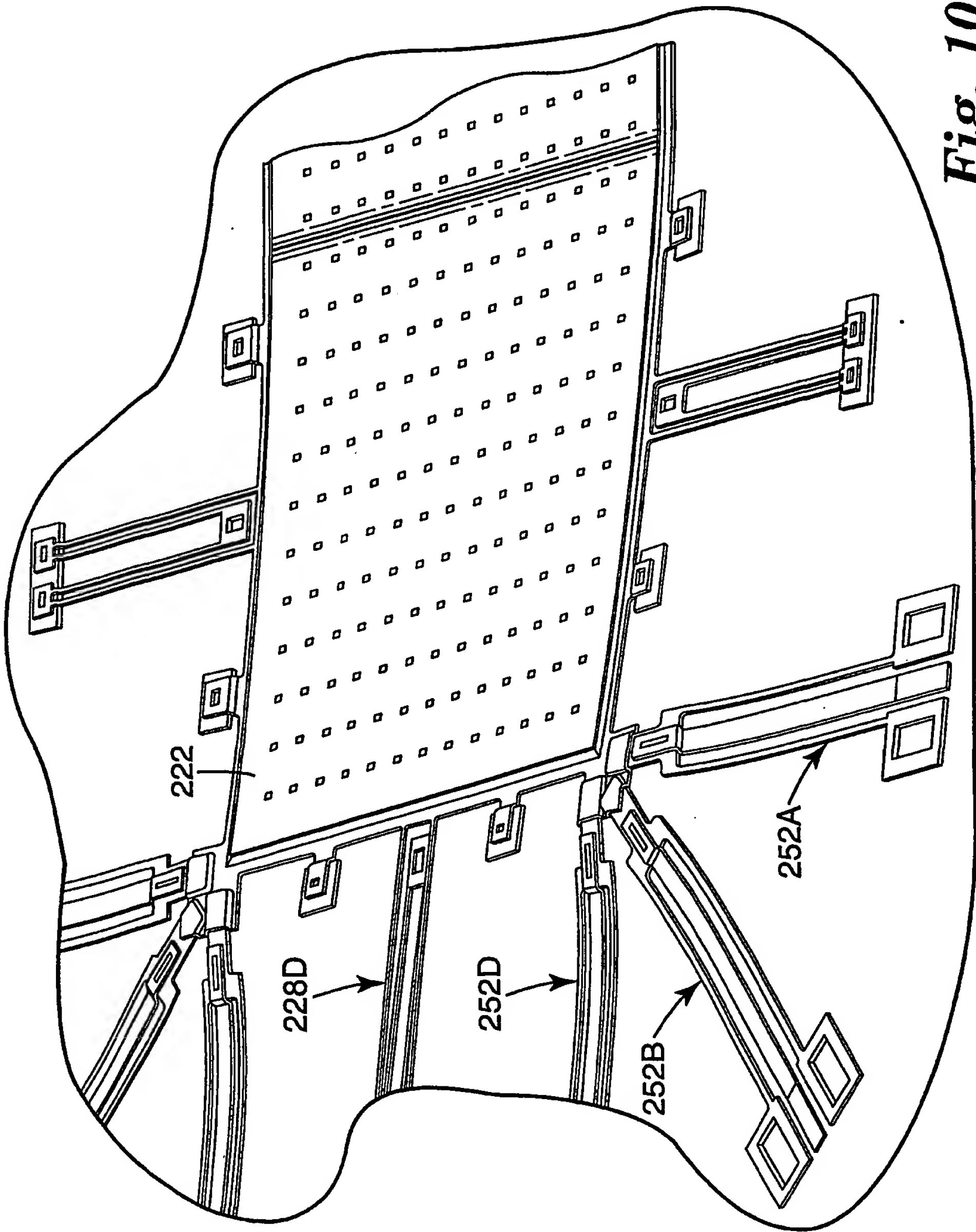


Fig. 10

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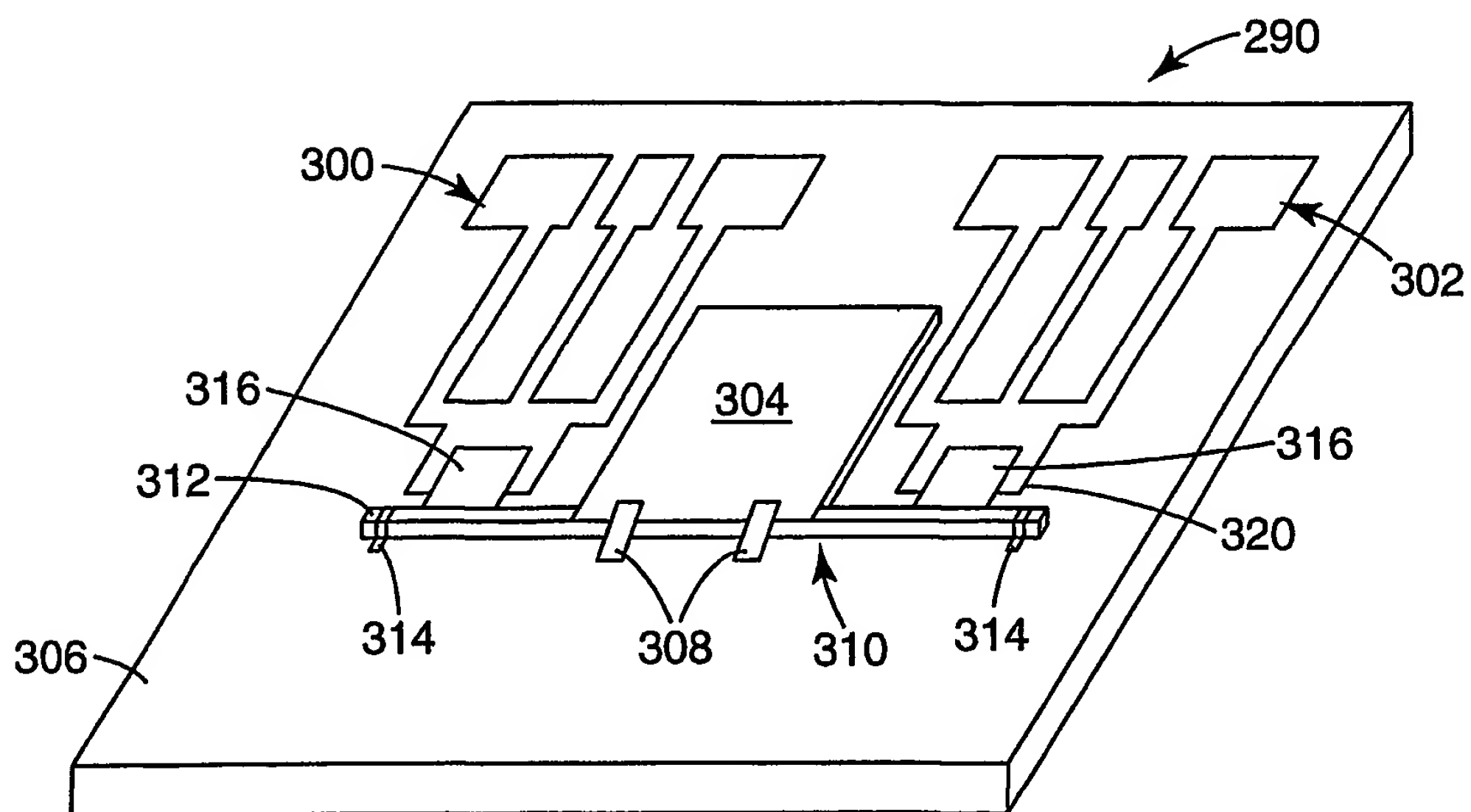


Fig. 11

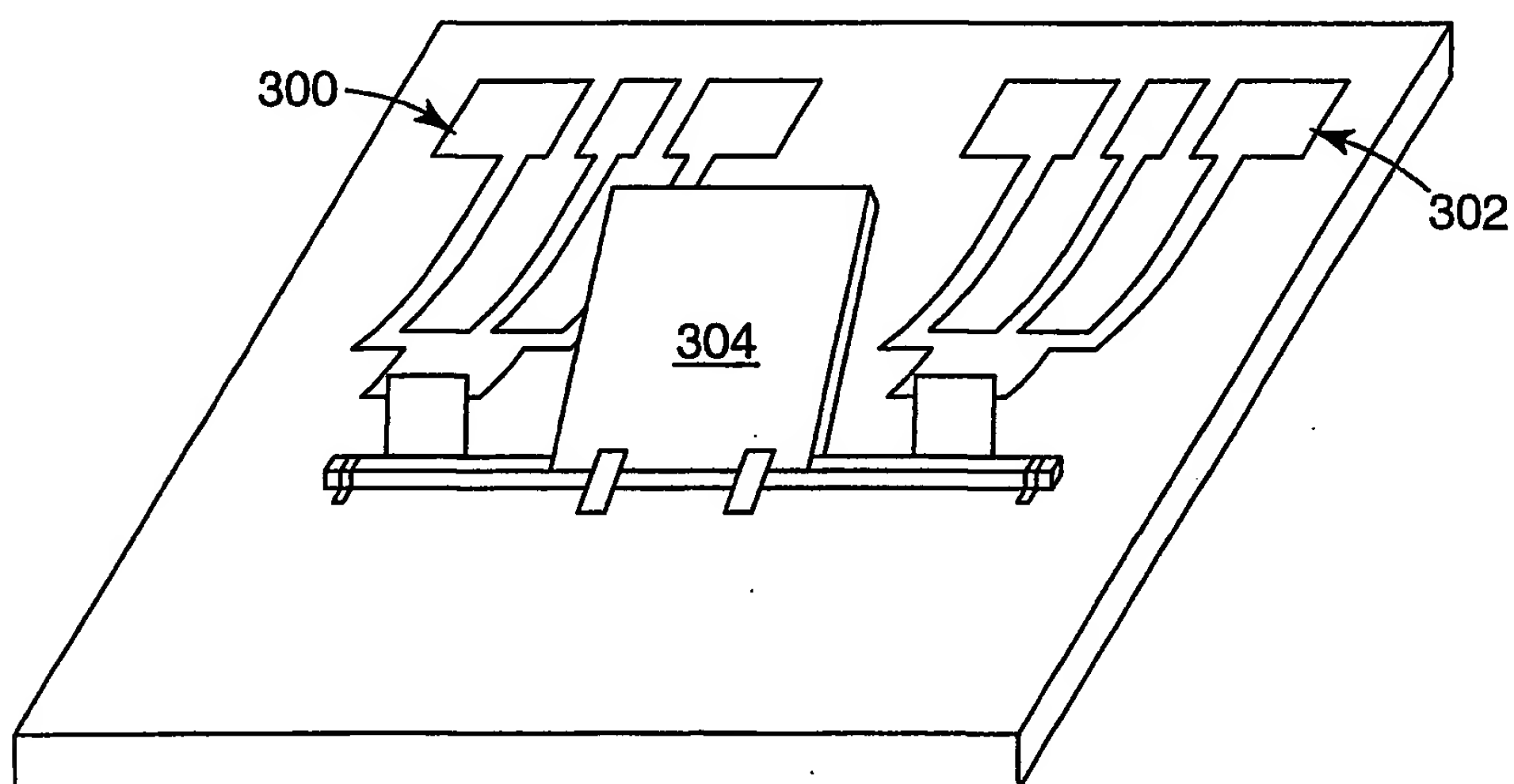


Fig. 12

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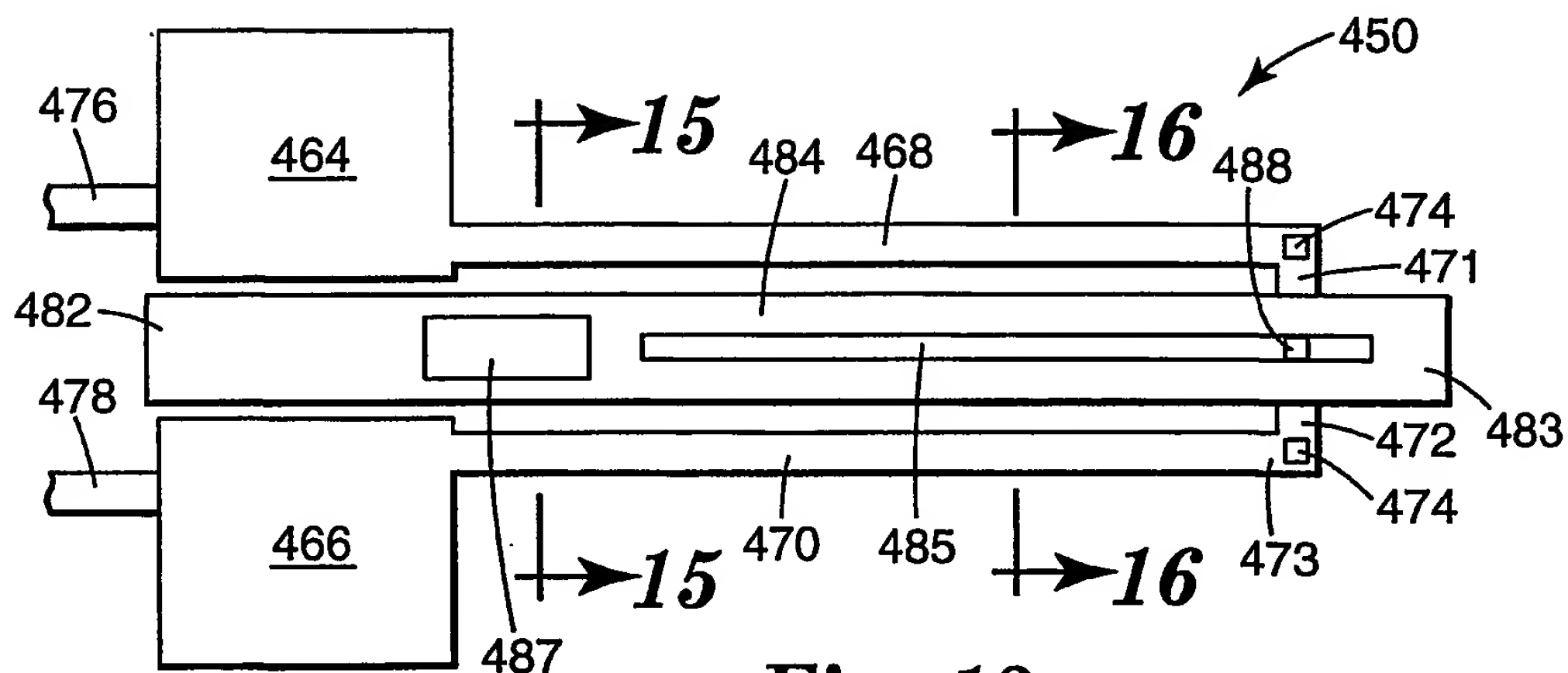


Fig. 13

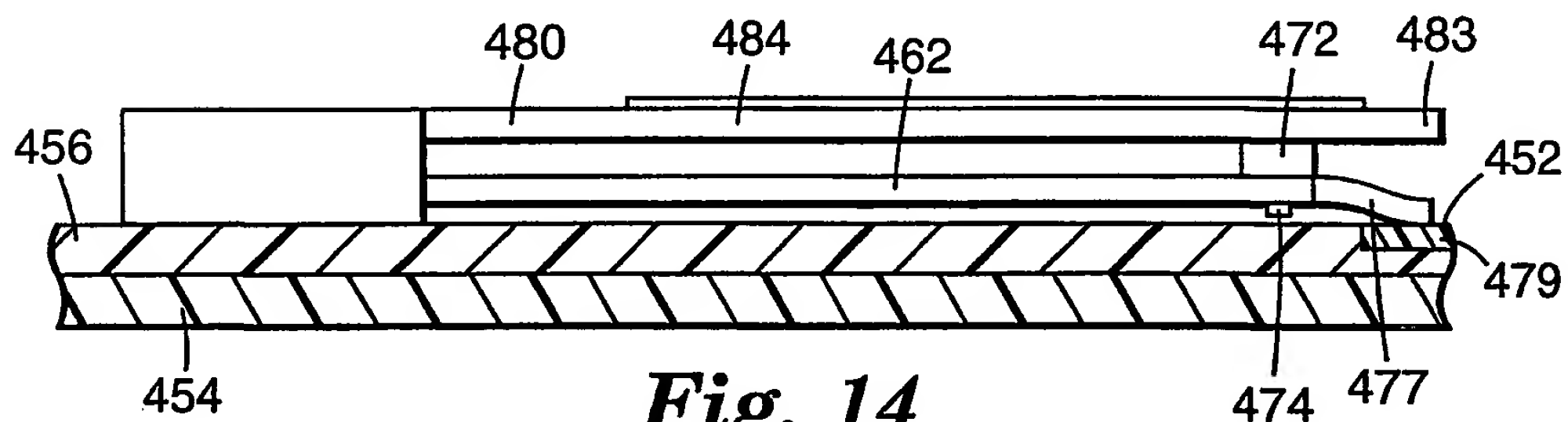


Fig. 14

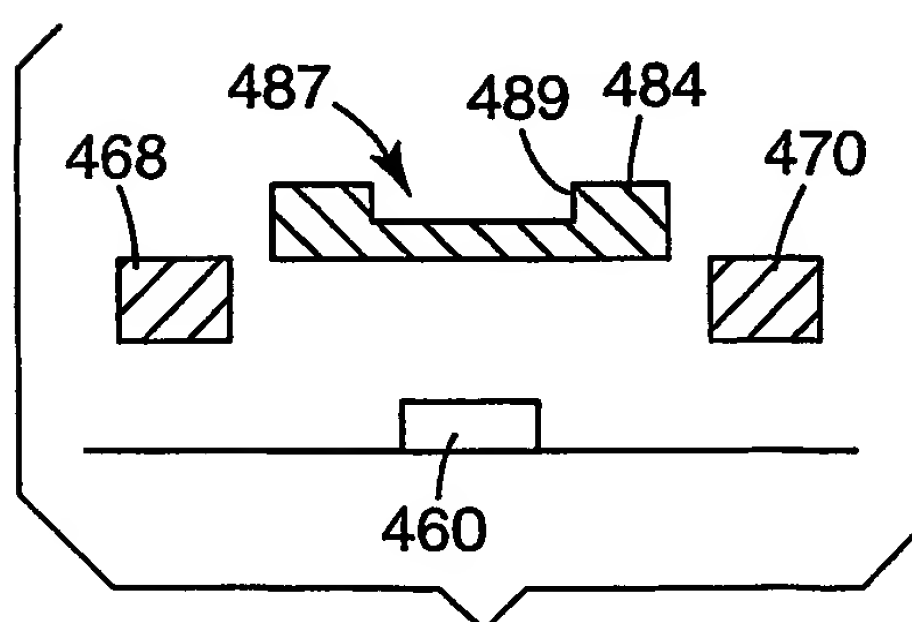


Fig. 15

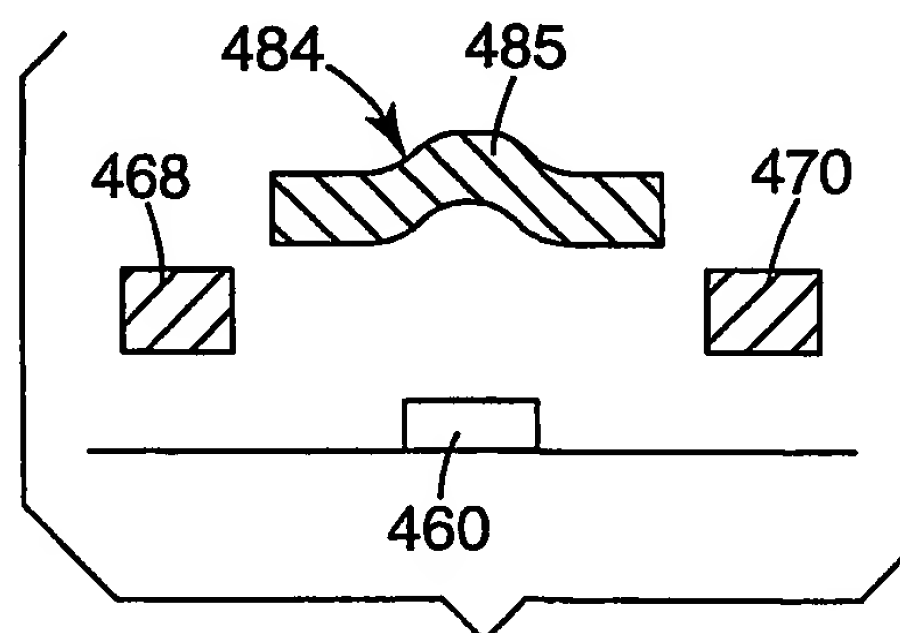
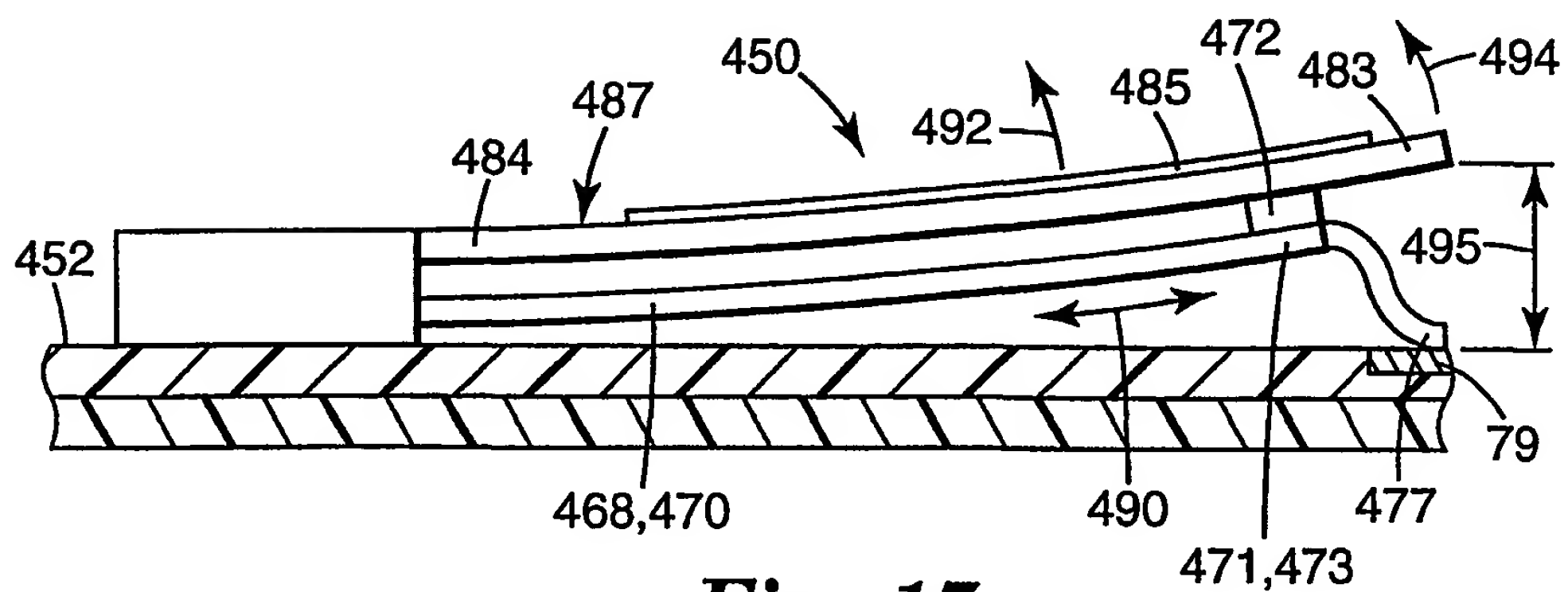
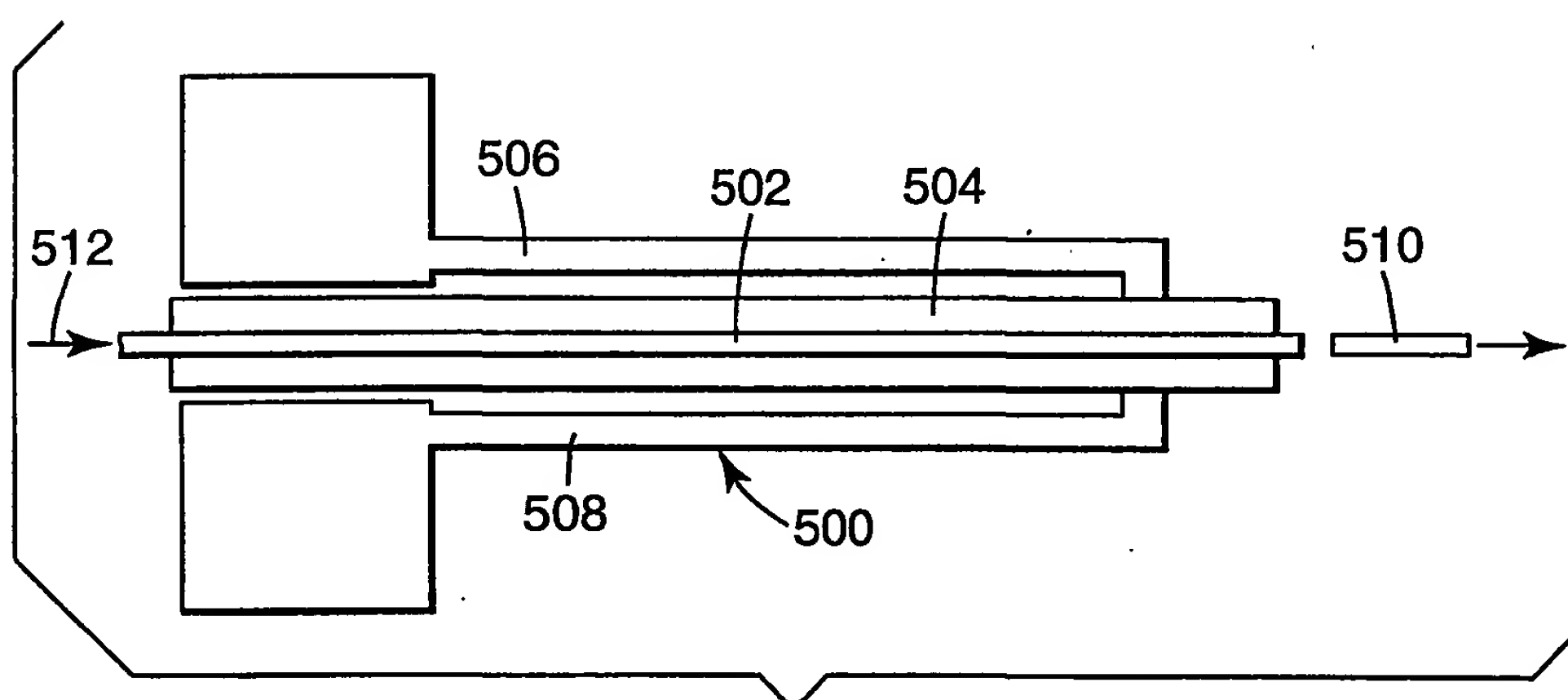
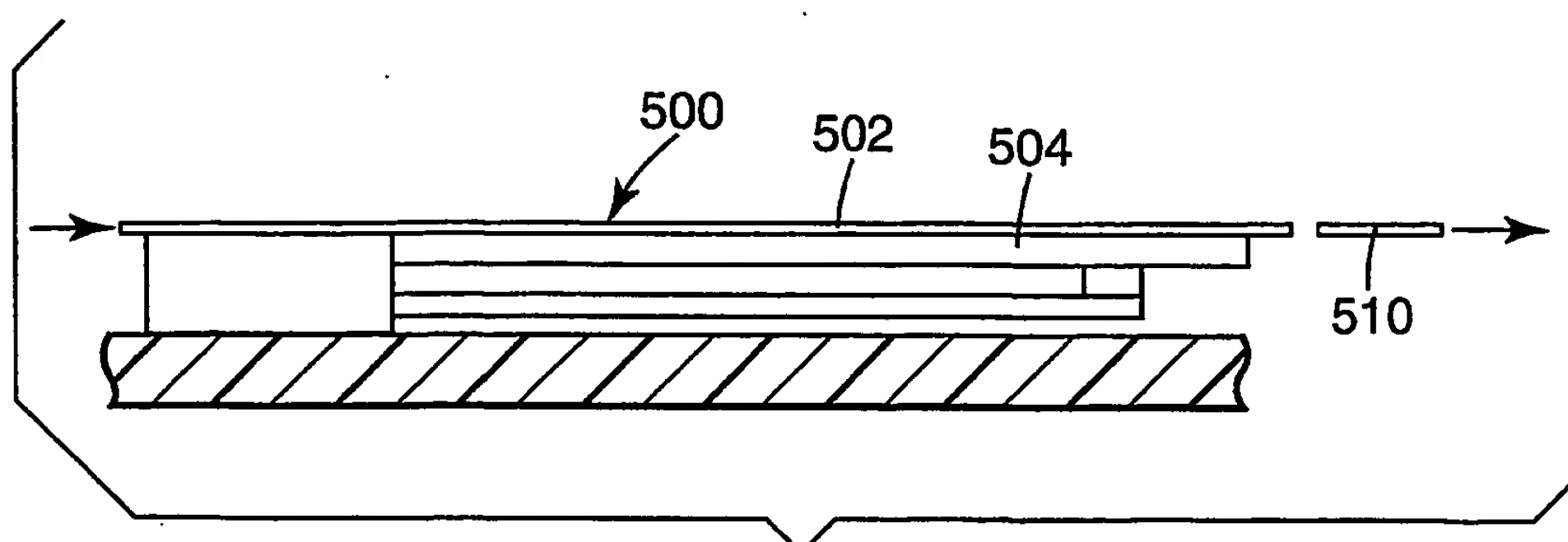


Fig. 16

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**Fig. 17****Fig. 18****Fig. 19**

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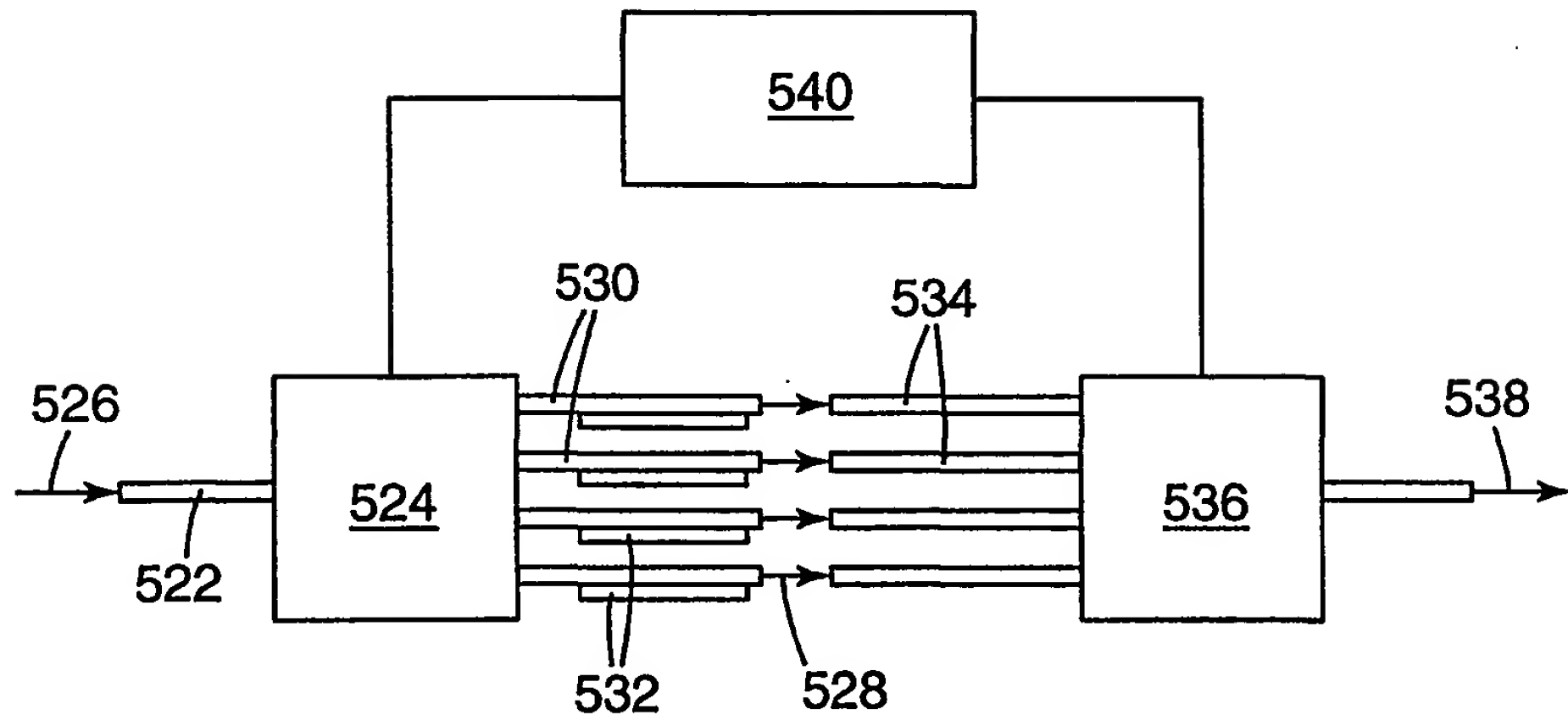


Fig. 20

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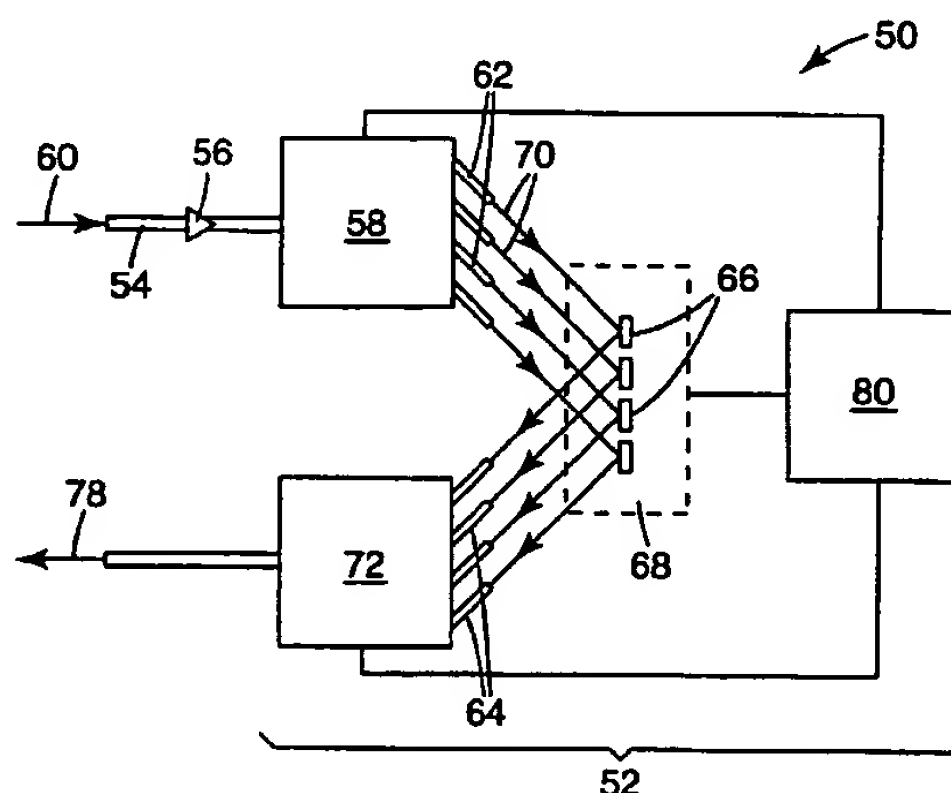
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[Continued on next page]

(54) Title: MEMS-BASED WAVELENGTH EQUALIZER



(57) Abstract: A wavelength specific optical equalizer for selectively attenuating discrete wavelength signals contained within a wavelength division multiplexed signal without affecting the adjacent signals. The wavelength equalizer includes a demultiplexer adapted to separate a wavelength division multiplexed signal into a plurality of discrete wavelength signals and to direct each of the discrete wavelength signals along a plurality of first optical paths. A micro-mechanical device comprising at least one micro-mirror is optically coupled with each of the first optical paths. A plurality of second optical paths is positioned to receive the discrete wavelength signals reflected from the respective micro-mirrors. At least one actuator is mechanically coupled with each of the micro-mirrors. The actuators are adapted to selectively displace one or more to divert at least a portion of the discrete wavelength away from the corresponding second optical paths. The orientation of the micro-mirror determines a signal strength of the discrete wavelength signal reflected to the corresponding second optical path. A multiplexer is provided to combine the discrete wavelength signals in the plurality of second optical paths into a reconstituted wavelength division multiplexed signal.

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INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 01/42504

A. CLASSIFICATION OF SUBJECT MATTER

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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H04B G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GILES C R ET AL: "A SILICON MEMS OPTICAL SWITCH ATTENUATOR AND ITS USE IN LIGHTWAVE SUBSYSTEMS" IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, IEEE SERVICE CENTER, US, vol. 5, no. 1, January 1999 (1999-01), pages 18-25, XP000823383 ISSN: 1077-260X page 24, column 1; figure 14	1,3,8, 16-19,25
Y	---	2,4-7, 9-15, 20-24
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Patent family members are listed in annex.

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- *G* document member of the same patent family

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 01/42504

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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